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U.S. Nuclear Regulatory Commission
Attn: Document Control Desk
Washington, D.C. 20555

Subject: "Introduction to the Pebble Bed Modular Reactor"

Dear Sir/Madam,

Transmitted here with is a copy of the subject document, which provides a general description of the Pebble Bed Modular Reactor (PBMR). This document presents an overview of the PBMR; the concept, the basic principles of design, safety analysis, and operation. It is not intended to be used (or maintained) as a design document.

Sincerely,

Kevin F. Borton
Manager, Licensing

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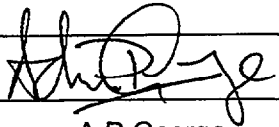# INTRODUCTION TO THE PEBBLE BED MODULAR REACTOR (PBMR)

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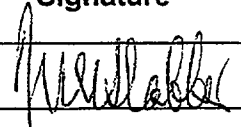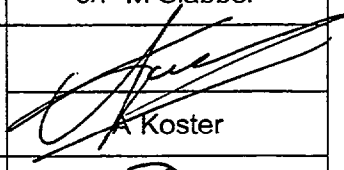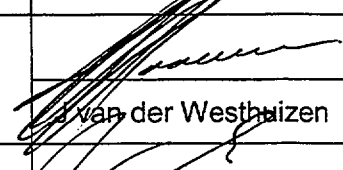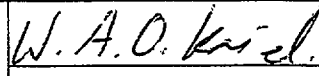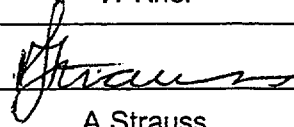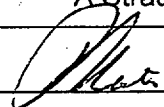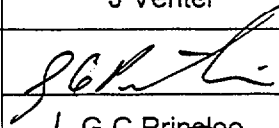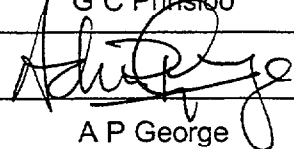
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CONTENTS

FIGURES

TABLES

LIST OF ABREVIATIONS

Abbreviation or Acronym	Description
ACS	Active Cooling System
ALARA	As Low As Reasonably Achievable
AVR	Arbeitsgemeinschaft Versuchsreaktor (Jointly-operated Prototype Reactor)
Bq	Becquerel
CAS	Compressed Air System
CCGT	Closed Cycle Gas Turbine
CCS	Core Conditioning System
CIS	Control and Instrumentation System
CRDM	Control Rod Drive Mechanism
CRV	CCS Recuperator Bypass Valve
DLOFC	Depressurized Loss of Forced Cooling
DS	Decontamination System
EHS	Equipment Handling System
EMB	Electromagnetic Bearings
EPS	Equipment Protection System
FDAS	Fire Detection and Alarm System
FHSS	Fuel Handling and Storage System
FPS	Fire Protection System
GWd/t	Gigawatt Days per Tonne
h	Hour
He	Helium
HEPA	High Efficient Particulate Airfilter
HICS	Helium Inventory Control System
HMI	Human-machine Interface
HMS	Helium Make-up System
HP	High Pressure
HPC	High Pressure Compressor
HPS	Helium Purification System
HPT	High-pressure Turbine
HPTU	High-pressure Turbo-unit
HPTC	High-pressure Turbo-unit Compressor
HTR	High Temperature Reactor
HTR-Modul	High Temperature Modular Reactor
HVAC	Heating, Ventilation and Air-conditioning
ICS	Inventory Control System
ILTI	Inner Low Temperature Isotropic
kPa	Kilopascal
LEU	Low Enriched Uranium
LEU-TRISO	Low Enriched Uranium – Triple Coated Particle
LOCA	Loss of Coolant Accident

Abbreviation or Acronym	Description
LP	Low Pressure
LPC	Low-pressure Compressor
LPT	Low-pressure turbine
LPTU	Low-pressure Turbo-unit
LWR	Light Water Reactor
MCB	Metallic Core Barrel
MCLR	Metallic Core Lateral Restraint
MCR	Maximum Continuous Rating
MCSS	Metallic Core Support Structure
MES	Module Electrical System
MPS	Main Power System
MSS	Main Support Systems
MWd/t	Megawatt Days per Tonne
NPP	Nuclear Power Plant
OCS	Operational Control System
OLTI	Outer Low Temperature Isotropic
PB	Pressure Boundary
PBMR	Pebble Bed Modular Reactor
PCU	Power Conversion Unit
PCUPV	Power Conversion Unit Pressure Vessel
PCV	Pre-cooler Vessel
PEI	Post Event Instrumentation
PLICS	Primary Loop Initial Clean-up System
PPB	Primary Pressure Boundary
PPSB	Power Plant Services Building
PSIA	Pounds per Square Inch Absolute
PT	Power Turbine
PTG	Power Turbine Generator
PWR	Pressurized Water Reactor
RCCS	Reactor Cavity Cooling System
RCS	Reactivity Control System
RCSS	Reactivity Control and Shutdown System
RP	Radiation Protection
RPS	Reactor Protection System
RPV	Reactor Pressure Vessel
RPVCS	Reactor Pressure Vessel Conditioning System
RSS	Reserve Shutdown System
RU	Reactor Unit
RUCS	Reactor Unit Conditioning System
s	Second
SAS	Small Absorber Sphere
SBS	Start-up Blower System

Abbreviation or Acronym	Description
SiC	Silicon Carbide
THTR	Thorium High-temperature Reactor
TRISO	Triple Coated Particles
UFCS	Used Fuel Cooling System
UHSS	Ultimate Heat Sink System
VDU	Video Display Unit
WHS	Waste Handling System

KEY NON-APPLICABLE LIGHT WATER REACTOR TERMS

The following terms commonly used in connection with Light Water Reactors (LWR) are not directly applicable to the Pebble Bed Modular Reactor (PBMR). It is suggested that their use be avoided to avoid confusion.

ATWS – Since the failure of the negative temperature coefficient is not possible, it can therefore not be postulated in combination with failure to insert control rods and failure to insert reserve shutdown spheres.

LOCA – Loss of coolant is not physically possible. Depressurization events should be described as such and not loosely fit under the term LOCA.

Core Damage Events – In a Light Water Reactor, core damage is essentially synonymous with core melting; core melting is not possible in the PBMR.

Coolant – The terms coolant, primary coolant, and pressure boundary are used in connection with the PBMR. However, the context is significantly different to LWR usage.

The term 'coolant', when used in an LWR context, implies keeping the core cool in order to avoid fuel damage; an urgency or immediacy is associated with this function (prevent fuel damage). Maintaining the primary coolant 'pressure boundary' is a critical safety function.

The function of the pressure boundary in the PBMR is to contain the helium that removes heat from the core and transfers the energy to the Power Conversion Unit (PCU). The critical safety function of the PBMR pressure boundary is to provide structural support to ensure the core geometry is physically maintained under normal and postulated accident conditions. Loss of helium does not result in fuel damage.

1. GENERAL DESCRIPTION AND TECHNOLOGY OVERVIEW

1.1 Introduction

This document provides an introduction to Pebble Bed Modular Reactor (PBMR) technology. It presents an overview of the PBMR; the concept, basic principles of design, safety analysis, and operation. It is not intended to be used (or maintained) as a design document.

It is expected that this document will be used by individuals with a technical background in power generation, from Exelon and their PBMR (Pty) Ltd partners.

This document was developed by extracting information from other PBMR documents that are in various stages of completion. Some discrepancies in terminology and details may therefore exist as the design process evolves.

1.2 General Description

1.2.1 Technical design philosophy

The fundamental concept of the design of the PBMR is aimed at achieving a plant that has no physical process that could cause a radiation hazard beyond the site boundary. This is principally achieved in the PBMR by demonstrating that the integrated heat loss from the reactor vessel exceeds the decay heat production in the post-accident condition, and that the peak temperature reached in the core during the transient is below the demonstrated fuel degradation point, and far below the temperature at which the physical structure is affected. This is intended to preclude any prospect of a core melt accident. Waste heat removal from the reactor vessel is achieved by active means during normal operation, and by passive means should the active system fail.

The PBMR module is the smallest standalone component of the PBMR power generation system. The module is a power station that can produce approximately 110 MW of electrical power. This module can be used to generate power in a standalone mode, or as part of a power plant that consists of up to 10 units.

The PBMR is a graphite-moderated, helium-cooled reactor that uses the Brayton direct gas cycle to convert the heat, which is generated in the core by nuclear fission. The heat is transferred to the coolant gas (helium), and converted into electrical energy by means of a gas turbo-generator. The PBMR core is based on the German high-temperature gas-cooled technology, and uses spherical fuel elements.

Any concern of fire in the graphite core is avoided by showing that there is no method of introducing sufficient oxygen into a high temperature (> 1 000 °C) core to achieve sustained oxidation. This is achieved primarily by the structural design of the reactor structure and building.

The use of helium as a coolant, which is both chemically and radiologically inert, combined with the high temperature integrity of the fuel and structural graphite, allows the use of high primary coolant temperatures (800 °C to 900 °C) which yield high thermal efficiencies. With these high temperatures, the use of a Closed Cycle Gas Turbine (CCGT) is justified. This increases the efficiency over a steam plant (from ~35% to ~45%), thus reducing the unit capital cost. It also removes external sources of contamination of the nuclear circuit, as there is no system with a higher pressure than helium. Without the possibility of leakage into the helium circuit, the need for on-line clean-up systems is largely reduced.
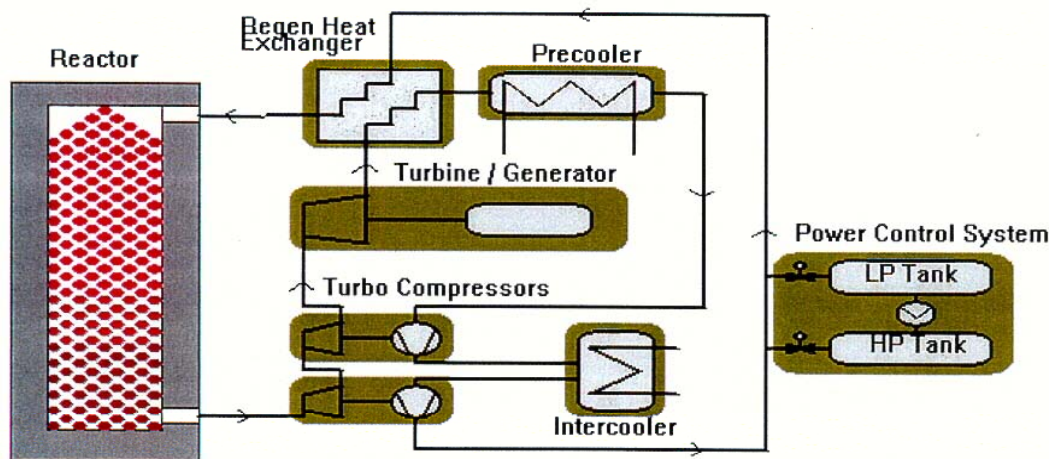
Figure 1: PBMR SYSTEM LAYOUT

1.2.2   Normal operation

At nominal rated full power conditions, helium enters the reactor at a temperature of approximately 500 °C (932 °F) and 70 bar (1 015 Pounds per Square Inch Absolute [PSIA]), and moves downward between the hot fuel spheres. It picks up the heat from the fuel spheres which have been heated by the nuclear reaction. The helium then leaves the reactor at a temperature of approximately 900 °C (1 652 °F).

The helium then moves through the High-pressure Turbine (HPT) and drives the High-pressure Compressor (HPC). Next, the helium moves through the Low-pressure Turbine (LPT), which drives the Low-pressure Compressor (LPC).

The helium then moves through the Power Turbine (PT) which drives the generator.

At this point, the helium is still at a high temperature. It passes through the recuperator in this state. Heat is transferred between the high temperature helium from the PT and the low temperature helium returning to the reactor.

The helium is now cooled by means of a pre-cooler. This increases the density of the helium and improves the efficiency of the compressor.

The helium is then compressed by the LPC.

The helium is cooled in the intercooler. This process increases the density and improves the efficiency of the compressor.

The HPC then compresses the helium.

The cold, high-pressure helium passes through the recuperator, where it is pre-heated. The helium then returns to the reactor.

Power output control is achieved by adding (or removing) helium to the circuit. This increases (or decreases) the pressures and mass flow rate without changing the gas temperatures or the pressure ratios of the system. The increased pressure and subsequent increased mass flow rate increases the heat transfer rate, thus increasing the power. Power reduction is achieved by removing gas from the circuit.

The power control system is supplied by a series of helium storage tanks ranging from low to high pressure to maintain the required gas pressure in the circuit. Adjustable stator blades on the turbo machinery and bypass flow are used to achieve short-term control.

During reactor shutdown, residual heat is removed by active and/or passive cooling of the system.

1.3 Key Features

Helium is radiologically nearly inert. The high levels of radiation in the core only activate the small percentage of He-3 in the gas.

Helium is also chemically inert and cannot react with any of the materials that are used in the construction of the PBMR.

The use of helium in a direct cycle gas turbine based PCU eliminates the requirement for a heat exchanger between a primary and secondary cycle. This improves the efficiency of the plant.

The PBMR fuel is based on a high quality German moulded graphite sphere containing coated fuel particles. The fuel particles (kernels) consist of uranium dioxide. Each kernel is coated with a layer of porous carbon, two high-density layers of pyrolytic carbon (a very dense form of heat-treated

carbon) with a layer of silicon carbide in-between. The porous carbon accommodates any mechanical deformation that the kernel may undergo during the lifetime of the fuel as well as fission products released from the kernel without over-pressuring the coated particle. The deformation of the kernel is due to the density changing, which is caused by fission products. The pyrolytic carbon and silicon carbide layers provide an impenetrable barrier containing the fuel and the radioactive products that result from the nuclear reactions.

These coated particles are embedded in a carbon matrix as a 50 mm sphere, called the fuel zone. Adding a 5 mm thick fuel-free graphite zone makes up the fuel sphere with an outer diameter of 60 mm. The fuel zone contains approximately 15 000 coated particles which contain 9 g uranium. A total of 330 000 fuel spheres and 110 000 pure graphite spheres are required for a single core loading.
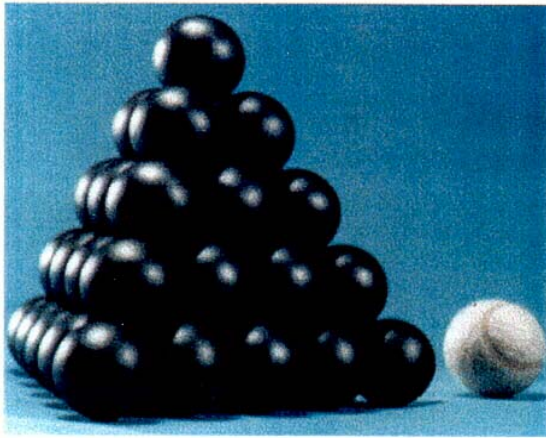
Figure 2: PBMR FUEL ELEMENTS

1.4   Technology

In the 1950s, Dr Rudolf Schulten (later Prof Dr Schulten, 'father' of the pebble bed reactor) had an idea. The idea was to compact coated uranium granules into hard billiard-ball-like graphite spheres to be used as fuel for a new high-temperature, helium-cooled type of reactor. The idea took root, and in due course, the AVR, a 15 MW (megawatt) demonstration pebble bed reactor, was built in Germany. It operated successfully for 21 years, in the later years using LEU TRISO coated fuel particles. Then, in the intense wave of post-Chernobyl anti-nuclear sentiment that swept Europe, particularly Germany, the idea was almost abandoned. It is resurfacing in South Africa.

The AVR Research Reactor and the Thorium High-temperature Reactor (THTR) were built in Germany to test the viability of this type of technology. The AVR Research Reactor was a 15 MW HTR based on the pebble bed concept. This reactor was used to both test and demonstrate fuel design, fuel loading configurations and HTR safety characteristics. Over its 21-year lifespan, the

C02

AVR Research Reactor reached a utilization factor of 70%. This means that 70% of its potential power was generated.

The THTR was a 300 MW reactor that was built to demonstrate the viability of different subsystem hardware designs with the emphasis on plant availability and maintainability. This plant had a designed lifespan of 40 years and reached an availability of 80% to 90%. The AVR reactor was a 40 MW thermal reactor, while the THTR was an 800 MW thermal reactor. This difference in size had various implications for the design of the THTR. Thus the THTR had:

- a larger core diameter (5 m);
- a concrete pressure vessel;
- in-core control rods; and
- active safety grade systems.

These changes were the result of a presumed need for larger reactor power levels. However, these changes also resulted in the vast majority of commissioning problems that the THTR experienced. The use of a concrete pressure vessel led to insulation difficulties, because concrete can only be allowed to reach a maximum temperature of 60 °C, and it needed to contain gases that reached temperatures of 650 °C. The next problem was due to the control rod insertion methods. The control rods needed to be inserted into the pebble bed by force. This resulted in damage to the fuel elements, which resulted in a lot of broken spheres, that in turn caused low availability of the fuel handling system.

Despite these problems, Pebble Bed HTR technology exhibited enormous potential. However, government funding issues and the Chernobyl disaster in 1986 led to the decision to close these research reactors. This was due to the immense pressure on the West German government to discontinue any nuclear activity.

In 1996, Eskom bought the PBMR licence from HTR (a joint venture of Siemens and ABB) in order to develop HTR technology into a viable and safe source of power. The South African PBMR team has already improved upon several of the design concepts of the THTR. For example, a steel pressure vessel has replaced the concrete pressure vessel, and control rods are now inserted in the reflector instead of the core. Furthermore, advances that have been made in gas turbine technology, have been incorporated into the PBMR design. The result is that the PBMR has built on these technologies to create a viable power plant.

2.   REACTOR UNIT

2.1   Introduction

The PBMR is a high-temperature, helium-cooled nuclear reactor with fully ceramic fuel elements and graphite as structural material. These ceramic materials are suitable for very high operating temperatures, hence enhancing the potential for achieving higher thermal efficiencies. As a coolant, helium has especially favourable characteristics: it is chemically inert, has a high thermal conductivity, and good neutron physics properties.

The reactor core consists of two zones. The inner zone that contains approximately 110 000 inert graphite spheres, and the outer zone (annulus) that contains approximately 330 000 fuel spheres. The nuclear reaction takes place in the core annulus and is controlled by the control rods that are housed in the side reflector of the reactor. Helium flows through the pebble bed and removes the heat generated by the nuclear reaction from the core. This helium is the same gas that is used as the working fluid in the PCU, hence the PBMR's direct gas cycle.

The function of the Main Power System (MPS) is to convert nuclear energy into electricity. This is done in two processes:

- the transfer of nuclear energy to gas at high temperature in the Reactor Unit (RU); and

- the conversion of the resultant thermal energy into electricity in the PCU, and the removal of excess energy to the ultimate heat sink.

The MPS is divided into two major subsystems, the RU and the PCU, directly coupled to each other. The MPS is located inside the citadel in the reactor building. This system is fundamentally the power production system of the module and includes the generator.

The Pressure Boundaries (PB) of the RU and PCU are welded together. The design provides for relative movement of the hot pipes inside the PB. The pipes are fixed at both sides and 'built-in' bellows and hinges in the pipelines allow for their relative movement.

The MPS is engineered such that the components that may need maintenance or replacement are easily or reasonably accessible. It is envisaged that the core structures will not need to be inspected or replaced. However, the system is laid out in such a way that it is possible to remove and replace the affected part of the core internals, if required. It is also possible to defuel the reactor (replacing fuel spheres with graphite spheres). The Fuel Handling and Storage System (FHSS) provides, or makes provision for, this function.

The time frame for defuelling is 48 h after the Brayton cycle has been stopped. For defuelling, it is required that the gas outlet temperature be below 400 °C and the pressure below 500 kPa (limiting pressure for opening the graphite sphere tank and storage tank).

2.2   Major Features and Internal Components

2.2.1   Reactor pressure vessel

The internal volume of the Reactor Pressure Vessel (RPV) is separated from the internal volume of the Power Conversion Unit Pressure Vessel (PCUPV) by means of a separation structure. This separation is necessary to maintain the RPV wall at a temperature different to that of the PCUPV. These two vessels are pressure connected, and no differential pressure will exist over this separation structure.

During normal operation, the RPV wall temperature is maintained at between 280 °C and 300 °C by means of a combination of the heat transfer design of the core structures, the Reactor Unit Conditioning System (RUCS) and Reactor Cavity Cooling System (RCCS).

The main function of the RPV is to contain the high-pressure helium, provide support and alignment for the core structures and their subsystems, and maintain core geometry within acceptable limits, under all normal and postulated abnormal conditions.

The RPV consists of a main cylindrical section with torispherical upper and lower heads. The upper head is bolted to the cylindrical section and incorporates penetrations for the mechanisms of the Reactivity Control System (RCS), Reserve Shutdown System (RSS), and for the in-core instrumentation. An opening is provided in the centre of the upper head to allow access to the upper core structures.

The lower head is welded to the main cylindrical section, and will have openings for the FHSS and the RSS, a large opening for the Fuel Discharge System, and an opening for access to the bottom core structures. This access opening is intended for use only during initial installation operations.

The shell flange at the top of the vessel accommodates the studs for bolting down the Pressure Vessel closure head. The studs are of the scant shank type, screwed into blind tapped holes in the flange ring.

The RPV has an internal diameter of 6.2 m and a nominal thickness of 120 mm. The top and reinforced parts have a thickness of 220 mm. The vessel head has an internal radius of 3.8 m and a nominal thickness of 140 mm, and for the bottom dome, these measurements are 5.23 m and 120 mm respectively. The maximum external diameter of the RPV is approximately 7 m (over

vessel head flange) and its total length is approximately 21.88 m. The mass of the RPV with the vessel head is estimated at 724 t.

The nuts and washers have convex mating surfaces in order to ensure favourable load distribution. Welded-lip seals provide leak tightness. The core structure is vertically supported at the bottom by a forged ring that is part of the bottom dome.

The RPV is insulated, except for the part that corresponds to the height of the core. This is to passively transmit core heat from the reactor to the RCCS.

The RPV shall be manufactured using carbon steel SA 533 Type B Class 2 for plates, SA 508 Type 3 Class 2 for forgings and SA 540 Grade B4 Class 3 for bolts.

Embrittlement of the RPV material due to neutrons cannot be excluded, but is anticipated to be less severe than that in currently operating Pressurized Water Reactors (PWR). This will be fully addressed as soon as the expected neutron dose is determined. Since the PBMR RPV is operated at the same wall temperatures as the PWR, the existing worldwide materials database on neutron embrittlement may also be applicable.

2.2.2   Core structures

The reactor core structures consist of the Ceramic Core Reflector, the Metallic Core Lateral Restraint (MCLR), and the Metallic Core Barrel (MCB). **Figure 3** illustrates the layout of the reactor core structures.

The functions of the core structures are to:

- provide and maintain the geometry of the pebble bed;
- provide and maintain a flow path for fuel and graphite spheres;
- provide and maintain openings for the Reactivity Control and Shutdown System (RCSS);
- provide inlet and outlet flow paths for the helium coolant;
- provide neutron reflection by bottom, side, and top reflectors;
- provide neutron and gamma shielding; and
- provide thermal insulation.

The pebble bed core cavity is a cylinder 3.5 m in diameter, with an equivalent pebble bed height of 8.5 m. There is a cavity above the core with an equivalent height of 500 mm. The lower section of the core cavity has a conical section with an angle of 30° to facilitate free movement of the fuel and graphite spheres.

Reactivity Control System

Reserve Shutdown System

Top Reflector

Gas Flow Channel

Reactor Pressure Vessel

Side Reflector

Core Barrel

Inlet Plenum

Bottom Reflector

Outlet Plenum
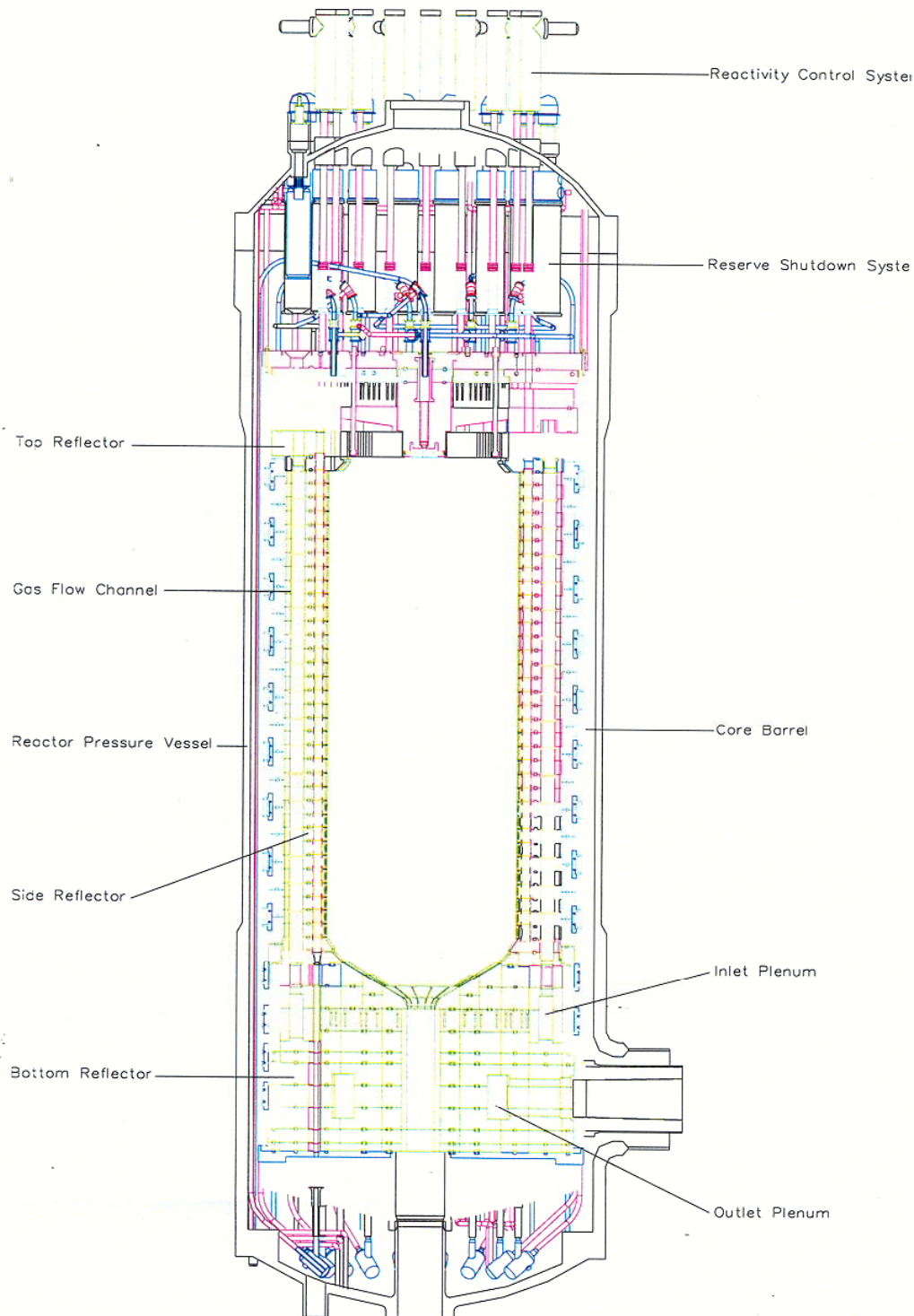
Figure 3: REACTOR PRESSURE VESSEL AND INTERNALS

C03

The pebble bed core cavity is formed by the ceramic core reflector, which consists of a lower structure, an annular side structure and a top structure.

The ceramic core reflector is a 36-sided right prism, approximately 15 m high, with an outer diameter of 5.5 m. It consists of an inner section of graphite blocks adjacent to the fuel pebbles, and an outer section blocks on the side and bottom, for thermal insulation. Thermal insulation above the reactor core is provided by a carbon layer attached to the inner surface of the MCB top plate.

The MCB is a steel cylindrical shell that sits within the RPV, and is supported and located by the Metallic Core Support Structure (MCSS). It has a stiffening ring at the top, and upper radial bearings that locate with the RPV. This bearing does not prevent relative vertical movement between the MCB and the RPV.

The MCB provides horizontal support to the ceramic core reflector and pebble bed via the MCLR. It provides vertical support via the stiff structure at its base.

The MCB is located on bearings supported by the lower hemispherical head of the RPV.

2.2.2.1 Ceramic core reflector structure

The ceramic core reflector structure consists of an inner cylinder of high-quality graphite blocks surrounded at the bottom and on the sides by carbon blocks.

The inner and outer reflector structure is designed as 36 vertical columns. The layout of blocks in the region of the core is shown in **Figure 4**. The blocks within a column are connected vertically via a dowel system. Azimuthally, the inner graphite blocks are located within the carbon blocks via a radial keying system.

The core reflector design philosophy is to ensure that individual columns can expand thermally and accommodate irradiation-induced dimensional changes, independent of adjacent columns, under all normal operating conditions and most upset conditions.

Essentially, no reflector block should be supported by more than one block to prevent load transfer from column to column, or 'ratchet-type' progressive deformation. The design of the columns includes provision for all-round gaps in plan view, which leads to continuous vertical gaps between columns.

Systems of sealing keys are used between columns to prevent gas leakage between radial sections of the ceramic reflector core structure, e.g. from the inlet plenum to the outlet plenum.

The 36 inner reflector columns have bore holes, 35 of which accommodate the RCSS. These bore holes have a diameter of 130 mm, and are located on a pitch centre diameter of 1 875 mm. The Reactivity rod bore holes penetrate the side reflector to a depth just below the core. The RSS bore holes pass the core. The layout of the systems is shown in **Figure 3**.

The ceramic core reflector structure can be split into three sections:

- the bottom reflector structure;

- the side reflector structure; and

- the top reflector structure.

a. Bottom reflector structure

The bottom reflector structure provides the following essential functions:

- neutron reflection;

- pebble bed support;

- fuel discharge;

- side reflector support;

- connectivity to the MCB;

- direction, containment and separation of the inlet and outlet gas flows;

- thermal insulation;

- neutron shielding; and

- bore holes for the RCSS.

The bottom reflector extends from the base of the MCB to the outer edge of the conical section at the base of the pebble bed core.

The lower section of the bottom reflector comprises an inner zone of graphite blocks arranged in 36 segments, and an outer zone arranged in 12 segments.

The bottom layer of blocks is offset relative to the remainder of the column, to prevent the continuous vertical gaps from the hot and cold plenums from coming into direct contact with the bottom metallic support structures.

These bottom blocks are held in place relative to each other, and relative to the bottom metallic structures, by dowels.

The conical section beneath the pebble bed core is formed by bevelled top blocks at an angle of 30°. The blocks are radially keyed together.

One layer of graphite blocks beneath the pebble bed contains B_4C pins to minimize neutron activation of metallic structures beneath the core, and reduce neutron streaming down the gas ducts to the PCU or the Core Conditioning System (CCS).

The lower graphite layers of the bottom reflector house the inlet plenum and connecting passages to the PCU and CCS. The upper graphite region of the bottom reflector houses the outlet plenum and connecting passages to the PCU and CCS.

b.   Side reflector structure

The side reflector structure provides a number of essential functions:

- neutron reflection;

- pebble bed support;

- support for the top reflector;

- flow passages for the inlet helium;

- neutron shielding;

- heat removal/control path; and

- bore holes for the RCSS.

The side reflector extends from the top of the bottom reflector, up the full height of the pebble bed, to just below the insulation on the inner side of the MCB top plate.

In order to avoid the formation of stable lattices of spheres (clustering) during their movement along plane surfaces, the inner flow surfaces on the lower section of the core cavity are provided with dish-like indentations (10 mm deep) to enhance a random distribution of the fuel spheres.

Sealing keys between columns are used to prevent gas leakage from the inlet bore holes to the core. These keys will also provide stability during an abnormal load, e.g. a seismic event.
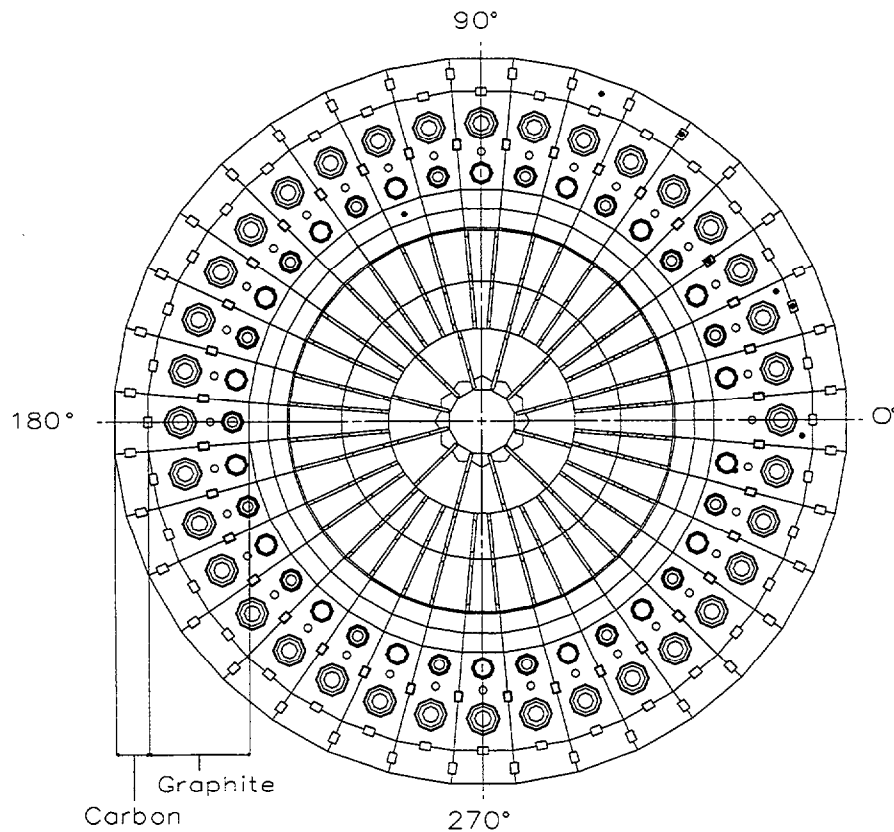
Figure 4: LAYOUT OF THE CORE REFLECTOR BLOCKS SHOWING SIDE AND BOTTOM REFLECTORS

Each of the inner 36 graphite blocks also contains a boring, 190 mm in diameter, to transfer the helium from the inlet plenum to the distribution chamber in the top reflector. The bore holes contain seals to minimize gas leakage.

The side reflector provides for fast neutron attenuation in order to limit damage to the MCB and RPV.

c.   Top reflector structure

The top reflector structure provides a number of essential functions:

- neutron reflection;

- helium inlet control and distribution;

- neutron shielding;

- thermal shielding;

- access for Control and Shutdown Systems;

- access for refuelling points;

- opening for the refuelling Gas Brake System; and

- possibility of access to the core via a removable central plug.

The top reflector consists of a central composite plug and a supported annulus of graphite between the central plug and the extended side reflector. The central composite plug is approximately 1 m in diameter, and is suspended from the MCB top plate. It contains the delivery guide and Gas Brake System for the central column graphite spheres.

The supported annulus has an inner diameter of 1 m and an outer diameter of 3 m. It is composed of 18 segments, each segment consisting of three layers of graphite, approximately 450 mm thick. Each of the 18 segments is supported by three tie rods.

The lower two layers house the distribution chamber for the inlet helium above the core. The lower layer contains holes to facilitate gas entry to the core from the distribution chamber.

Thermal insulation above the reactor core is provided by a carbon layer attached to the inner surface of the MCB top plate.

In addition to the 36 penetrations provided for the RCSS, nine fuel sphere handling tubes and one graphite sphere handling tube are connected to the outside of the upper surface of the MCB top plate.

2.2.2.2 Discharge tube

The discharge tube extends from the bottom of the conical section beneath the pebble bed to the FHSS connected to the bottom of the RPV. It consists of a graphite sleeve that extends from the MCB up to the inner bevelled reflector top block.

The lower part of the discharge tube consists of a metallic structure connected at one end to the MCB, and welded to the RPV at the other end.

2.2.2.3 Metallic core lateral restraint

The outer carbon blocks of the side reflector columns are prevented from excessive radial outward movement, due to thermal and irradiation deformation effects, by the core restraint props that are fixed to the MCB, and collectively form the MCLR. Each prop is located in a radial socket in, or between the carbon blocks, and is individually adjusted during the reflector assembly. The props therefore provide a degree of azimuthal restraint.

2.2.2.4 Metallic core barrel

The MCB comprises a reinforced cylindrical steel fabrication that is 5.85 m in diameter, 15.67 m high, and 50 mm thick. The function of the MCB is to restrain the side reflector columns (by means of the MCLR System) from excessive radial and azimuthal movements, to support the reactor top plate and to seal the reactor core from the annular space between the MCB and the RPV.

The bottom of the MCB comprises a reinforced steel plate that provides a flat base for the core assembly with minimal deflection.

The MCB is located coaxially within the RPV by the defuelling tube spigot. The core barrel is designed to withstand the pressure differential resulting from an equivalent 65 mm diameter pipe break in the RPV.

2.2.2.5 Metallic core barrel support bearings

The MCB is supported within the RPV by a series of roller bearings of the same design as those used in the THTR-300. These assemblies are equi-spaced around the periphery of the MCB. Each of these assemblies allows radial movement to accommodate differential thermal expansion, but prevent rotational movement. Pinions mounted on the upper and lower bearing blocks ensure free movement of the rollers, despite any tendency of the rollers to bond to the bearing blocks at the lines of contact.

Nine 240 mm diameter rollers, each with a bearing length of 556 mm, are used to support the reflector and core load. This combination is intended to keep contact stresses sufficiently low (approximately 600 MPa) to prevent any local yielding in the bearing blocks.

Temporary locking blocks will be fitted to the roller assemblies prior to the installation of the core barrel in the RPV, in order to prevent the assemblies from moving out of position. These blocks are removed manually after installation of the core barrel in the RPV.

2.3   Major Support Systems

2.3.1   Reactor cavity cooling system

The function of the RCCS is to dissipate the heat from the reactor during normal operation, including shutdown. The system also removes the decay heat during the loss of the heat transfer functions of the PCU (loss of forced cooling). The objective is to prevent the reactor vessel (including attachments), RPV supports, instrumentation and the concrete walls from exceeding their design temperature limits for all modes of operation. Natural processes, including thermal

radiation and convection, are relied upon to transport the heat from the non-insulated reactor pressure vessel walls to the cooling chambers of the RCCS.

Although the RCCS is classified as a safety system, no reliance is placed on it to protect the nuclear fuel from exceeding its maximum design temperature. The main purpose of RCCS is to protect the investment in building and systems, as without it, the reactor cavity wall and the RPV may temporarily exceed allowable temperature levels, precluding further use.

The RCCS includes three independent systems, each consisting of a low-pressure, closed-loop, pump-driven cooling system, with an internal water-to-water heat exchanger. Heat is transferred via these heat exchangers to an open water circuit, which then discharges the heat to an ultimate heat sink, which can be a large body of water or the atmosphere. Forty-five water chambers, each 500 mm in diameter and approximately 24 to 30 m long, depending on position, are arranged vertically side-by-side around the RPV. Every third chamber is connected to separate inlet and outlet headers to create the three independent cooling systems, each capable of absorbing 50% of the waste heat rejected by the pressure vessel. The water inlet pipes enter the chambers at the top, then run down inside the chambers to release the cold water at the bottom. In this way, a leak in an inlet pipe or header will not result in the chambers emptying. Anti-syphoning devices prevent the chambers being syphoned dry if a rupture occurs in the pipework outside of the reactor cavity.

The RCCS circuits contain demineralized water to which an inhibitor has been added to prevent the formation of scale or rust, which could become activated due to proximity to the core.

In the case where the closed loop pumps or heat exchangers are lost, mechanical draught cooling towers, situated on the roof of the module, automatically take over the cooling function of the systems. In the case where all the cooling units, including the cooling towers, are lost, the heat of the reactor is absorbed by heating up and then boiling off the water in the chambers. The low-pressure steam generated is released to the atmosphere from the module roof. The systems are sized to provide this cooling function for several days, but as a further back-up, water from the Fire Protection System (FPS) can be pumped into the chambers to replenish water lost by evaporation, thereby extending the time available for the passive cooling function.

A thin steel impingement shield is erected between the water chambers and the reactor. This shield serves to distribute the reactor heat evenly over the chambers, thereby preventing hot spots, and also serves to prevent water impinging onto the reactor should a leak occur in a chamber. The spaces between the chambers are closed off by means of steel plates, which are welded to one chamber while being allowed to slide against the adjacent chamber to accommodate differential movement. These inter-chamber plates prevent the hot air in the cavity from coming into contact with the concrete walls. The concrete floor of the cavity is insulated from the hot air.

2.3.2   Reactor unit conditioning system

The RUCS has three functions, it maintains the RPV at a desired temperature (280 °C to 300 °C) during normal power operation, it removes core heat during maintenance operations when the Start-up Blower System (SBS) cannot be used, and it can be used to recover the core from very hot conditions (up to 1 200 °C) in the event of a PCU trip (Brayton cycle is not operational) followed by failure of the SBS blowers to operate. During maintenance it is used to maintain the core at the required temperature, although the SBS blowers will be used to initially cool the core down to low temperature maintenance conditions.

Keeping the RPV at the desired temperature is achieved by blowing temperature conditioned helium. The gas exiting the RUCS blower units is collected in a manifold inside the RUCS vessel, and transferred via the outer annulus of the cold pipe leaving the RUCS, to a manifold in the bottom volume of the RPV. This manifold is connected to a system of 12 pipes, which run vertically in the annulus area between the RPV and the core barrel, to the RPV top volume. The manifold is attached to the RPV in the volume beneath the core support structure. The 12 connected distribution pipes are attached to the inner surface of the core barrel, which runs in the annulus area between the RPV and the core barrel. They therefore span the length from the bottom section of the RPV to the top section of the RPV. The gas thereafter flows downward along the inner wall of the RPV to keep it at the required temperature.

The second and third function is to remove core heat when the Brayton cycle or SBS blowers are not operational, in order to facilitate cooldown. It consists of a mixing chamber, recuperator, water cooler, blowers and a number of valves. The RUCS is directly coupled to the inlet and outlet plenums of the core via feed and return pipes that connect the RUCS pressure vessel to the RPV. The pressure boundary therefore forms a part of the Primary Pressure Boundary (PPB). The mixing chamber is used to reduce the temperature entering the recuperator. This is done by mixing cool helium from the water cooler with hot helium from the core outlet plenum. The recuperator reduces the temperature entering the water cooler and increases the temperature returning to the core. This is done in order to maintain a 400 °C delta in temperature between the core inlet and outlet plenums. The water cooler removes the required amount of core heat. The blowers provide the required amount of mass flow through the RUCS. The valves are divided between blower isolation valves and control valves, controlling mass flow through certain RUCS components.

2.3.3   Helium inventory control system

The Helium Inventory Control System (HICS) is made up of a number of subsystems:

- Inventory Control System (ICS);

- Helium Purification System (HPS);

- Helium make-up System (HMS).

2.3.3.1 Inventory control system

The Inventory Control System (ICS) has two functions: the control of pressure within the MPS, and, the storage of the primary coolant. The primary function of the ICS is to control the pressure within the MPS, which is done using the pressure differential between the MPS and the storage tanks. The pressure within the MPS is directly proportional to the power output of the reactor.

Helium is extracted from a higher-pressure part of the system, and injected into lower-pressure tanks, and vice versa. This control philosophy makes use of the system compressors to do most of the work to increase the pressure of the helium, in order to store it within the storage tanks.

ICS Process Flow Diagram
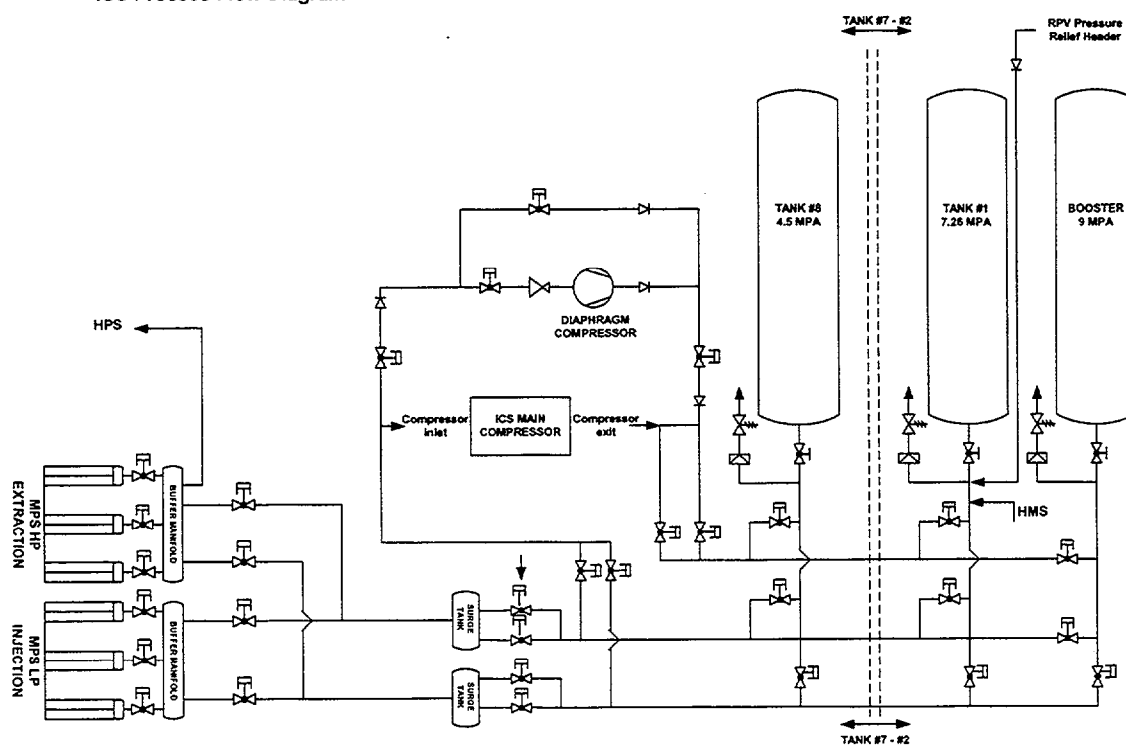
Figure 5: ICS PROCESS FLOW DIAGRAM

2.3.3.2 Helium purification system

The main purpose of the HPS is to purify the helium gas. The HPS bleeds off a partial flow of helium from a high-pressure point within the MPS (the same exit point used by the ICS). The HPS returns the purified helium to the generator casing. This is done in order to provide a slight over pressure in this volume, preventing unclean helium from passing through the generator shaft seals, and providing dust-free helium to this volume (preventing flash over).

The HPS function is done constantly during operation of the plant and removes the following gaseous contaminants:

- water;

- carbon monoxide;

- carbon dioxide;

- hydrogen;

- methane; and

- tritium.

The HPS is made up of the following components: a dust filter; a Copper Oxide Catalytic Converter; water cooler; chiller; water separator; molecular sieve; and an optional cryogenic loop which includes an activated carbon adsorber and liquid nitrogen cooler and recuperator.

2.3.3.3 Helium make-up system

The HMS replenishes the daily leakage of helium from the MPS. The HMS is comprised of the following components: standard off-the-shelf helium cylinders bundled into 16 packs of 18; a control valve for each cylinder pack; and a positive displacement compressor.
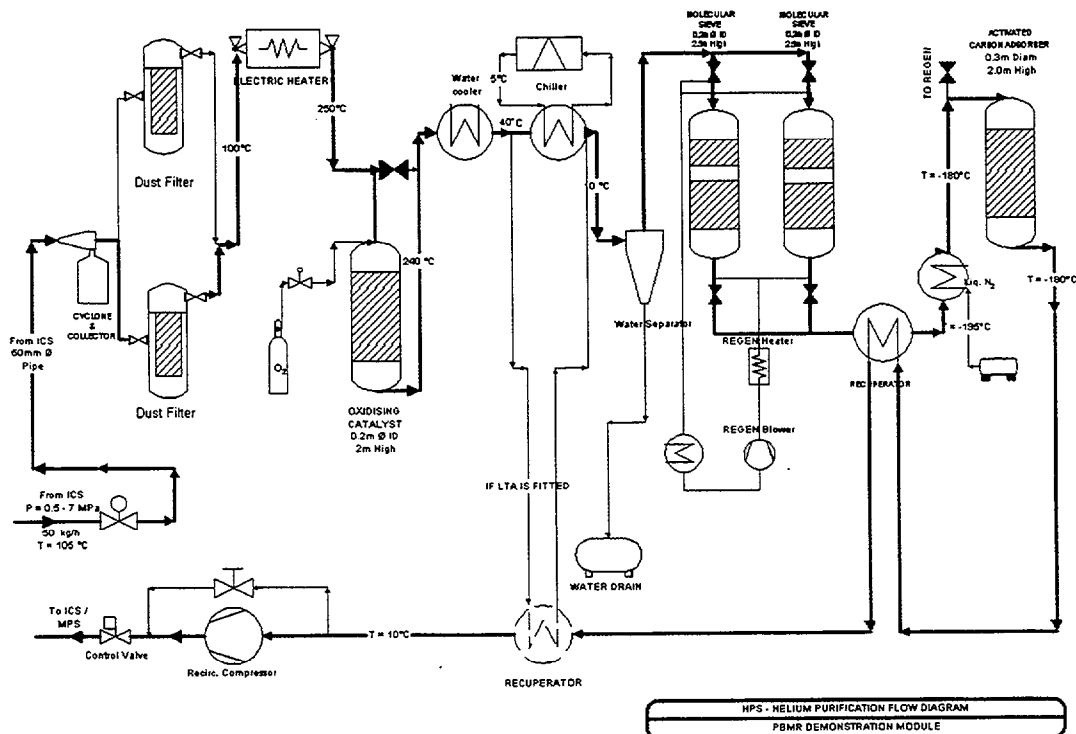
Figure 6: HPS – HELIUM PURIFICATION FLOW DIAGRAM

2.3.4 Fuel handling and storage system

The main purpose of the FHSS is to circulate the spherical fuel elements and graphite elements through the reactor core while the reactor is operating at power. The reactor core operates according to a 'multi-pass' fuelling scheme, which means that fuel spheres are moved through the core several times before reaching the desired burn-up.

The FHSS consists of the fresh fuel storage and feeding system, the fuelling and defuelling system including the discharge equipment, the spent fuel system, and the fuel lifting system. The storage system consists of the new fuel storage, graphite storage, spent fuel storage and the damaged fuel storage. The main parts of the fuel handling system are located in shielded, individual compartments below the reactor. The spent fuel storage, which is designed as a lifetime spent fuel store and post-operations intermediate store, is located in the lower part of the reactor building.

The fuel and graphite spheres are circulated by means of a combination of gravitational flow and pneumatic conveying using helium at MPS operating pressure, as the transport gas. The fuel spheres are circulated to the annulus of the reactor core and the graphite spheres are circulated to the central column of the core.

The FHSS also stores the spent fuel spheres discharged from the reactor core once these spheres have achieved their maximum burn-up, and feeds fresh fuel spheres to be circulated through the reactor core. The discharge of spent fuel and the feeding of fresh fuel are also performed at power. The handling and storage of spent fuel spheres are performed by means of pneumatic conveying using primary helium at MPS pressure and storage in helium at atmospheric pressure. Sufficient storage capacity is provided to store all the spent fuel generated by the reactor during the complete life of the PBMR module. The feeding of fresh spheres is performed by means of a combination of gravitational flow from the fresh fuel transport casks, and pneumatic conveying using helium at MPS pressure.

During reactor maintenance shutdown, the FHSS may be used to substitute the fuel spheres in the annulus of the reactor core with graphite spheres. The Used Fuel Storage Tank is designed for the interim storage of fuel spheres. This storage is in a helium environment.

3

FUEL HANDLING SYSTEM
SPHERE FLOW DURING NORMAL OPERATION

HIGH PRESSURE OPERATION

LEGEND:

(A)	DE-FUELLING MACHINE & SCRAP SEPARATOR & SCRAP CASK
(B)	RADIATION SENSOR AND INDEXER
(C)	DIVERTOR VALVE BLOCK TO SEPARATE FUEL & GRAPHITE
(E)	BURNUP SENSOR AND INDEXER
(F)	DIVERTOR VALVE TO SEPARATE USED & SPENT FUEL
(G)	TRANSFER VALVE BLOCK
(K)	COLLECTOR VALVE BLOCK
(I)	DISTRIBUTOR VALVE BLOCK
(L)	LOADING FACILITY
(D) (T)	GRAPHITE SENSOR & DISCHARGE LOCK
(S)	SPENT FUEL DISTRIBUTION

LOW PRESSURE COMPONENTS

SAMPLE COLLECTION UNIT (Q)

10 X SPENT FUEL STORAGE TANKS (Z)

FFHSS28f

Figure 7: FUEL HANDLING SYSTEM

C04

2.4 Reactivity Control and Shutdown System

The RCSS consists of two independent and diverse systems, namely:

- the RCS (control rods system); and

- the RSS.

The RCSS has the following functions:

- Each system must (independently be able to transfer the reactor to a subcritical state, and keep the reactor subcritical for an indefinite period at normal operating temperature.

- Both systems (combined) must allow the reactor to be in a subcritical state below 50 °C, and keep the reactor subcritical for an indefinite period of time at this temperature.

2.4.1 System description and drawings

2.4.1.1 Reactivity control system

The RCS consists of 18 control rod systems. The RCS is based on existing HTR/ABB technology and consists of the following (per system):

- control rod;

- Control Rod Drive Mechanism (CRDM), with position indicator; and

- rod emergency shock absorber.

The following descriptions relate to the drawings listed next to them:

Description	Drawing Number
RCS general layout drawing	**Figure 8**
RSS general layout drawing	**Figure 9**

a) Control rods

Each control rod consists of a number of segments containing absorber material in the form of sintered B_4C rings between two coaxial tubes.

Information will be provided that demonstrates that the components will survive the temperatures, fluxes and operational loads..

Gaps between the tubes and the B_4C rings prevent constraint forces due to radiation-induced swelling of the B_4C. Pressure equalizing openings expose the B_4C to the primary coolant.

The individual segments are joined together with a flexible coupling to form a single control rod.

The rods are freely suspended in the holes in the side reflector of the core internals. The annular clearance between the reflector and the rod is sufficiently large to prevent sticking of the control rods.

Both the inside and outside of the control rod are cooled by a leak stream from the cold helium inlet.

b) Control Rod Drive Mechanism

The main functions of the CRDM are to:

- raise and lower the control rods in the upper half of the core, and to hold them at any position in their travel range;

- guarantee insertion in the event of reactor scram (cutting power to the drive motors allows the rods to drop by gravity); and

- limit drop velocity and to absorb the kinetic energy of the falling rod when the rod reaches the lower travel range during a reactor scram condition.

The CRDM are integrated into the RPV top dome, and consist of the following main items:

- a link chain which connects the control rods with the gear of the drive mechanism;

- a stepper motor drive;

- a shock absorber;

- rod position indicators; and

- a rod holding mechanism (to hold the control in its upper position during replacement of the rod).

The control rod is moved up and down in the side reflector holes by a stepper motor. The stepper motor shaft is connected to a chain sprocket, which moves the link chain up or down. When the rods are raised, the link chain is stored in a loose pile in a box. When the rods are lowered, the link chain is drawn from the box.

c) Back-up shock absorber

In the postulated event of a rod drop due to mechanical failure of the drive parts or a chain break, damage to the ceramic core internals is prevented by a shock absorber installed inside the holes in the side reflector. The lower end of the rod, which is conically shaped for this purpose, centres on the top part of the shock absorber. The energy of the falling rod causes

plastic deformation of the concentric tubes beneath the top part of the shock absorber. After such an event, the shock absorber will be replaced.

d) Shielding

Provision will be made for adequate shielding using the As Low As Reasonably Achievable (ALARA) principle, for activities during maintenance operations.

2.4.1.2 Reserve shutdown system

A Small Absorber Sphere (SAS) shutdown system is provided as an RSS.

The RSS is completely different in design and materials to the control rods that form the RCS.

The RSS consists of 17 mutually independent SAS systems. The only shared component is a gas blower, which is used to remove the absorber spheres from the holes in the side reflector and to return them to the storage containers. The main functions of the RSS equipment are:

- to store the SAS, and ensure insertion on demand by releasing the shutdown spheres into the holes in the side reflector; and

- to remove the spheres from the holes in the side reflector, and transport them back to the storage containers.

The RSS design is based on an existing HTR-Modul technology, and consists of the following (per system):

- storage container (including release mechanism);

- discharge container;

- pipe connections;

- blower system; and

- shutdown spheres with a diameter of 10 mm and 10% B_4C content by volume in a graphite matrix.

The RSS components are mainly installed inside the RPV. The actuator for the storage container valve and Gas Blower System is, however, installed outside the RPV. The small spheres are stored in a storage container in the space underneath the RPV head. On demand, the storage container valve will open and the spheres will fall freely (under gravity) into the holes in the side reflector. In the event of the electrical supply to the magnetic valve being interrupted, the valve will fall open and the SAS will be released into the side reflector. Redundancy is built into the electrical supply to reduce the economic risk of shutting down the reactor unnecessarily. A pneumatic

system is used to return the shutdown spheres in controlled quantities from the hole in the side reflector.

A tube, of the same size as the hole in the side reflector, connects the reflector hole with the discharge container. During transport of the shutdown spheres, the spheres are separated from the gas stream by a cyclone, which is installed in the storage container. A capacitive level indicator in the storage container is used to detect the level of the spheres in the storage container. There are full and empty indication switches in the storage container.

Diverse and redundant methods will be employed to ensure that simultaneous removal of spheres of two or more columns of shutdown spheres in the side reflector is prevented.

A speed controller controls the capacity of the blower. This will ensure that forwarding of spheres will take place during all reactor conditions (gas density changes due to different reactor pressures and temperatures). Gas from the bottom of the RPV is used as transport gas.

The return pipes of the shutdown spheres and the gas suction pipes are installed on the outside of the core barrel. The gas pipes to the blower are connected to a valve bank at the bottom dome of the reactor.

2.4.2   Testing and inspection plan

2.4.2.1 Testing

As previously stated, the RCSS will be based on existing HTR technology. The number of changes to the existing designs to make it PBMR specific will determine the amount of test and qualification that will be required for this system.

2.4.2.2 Inspection/maintenance

The RCS and RSS components are designed for the full plant life. However, the CRDM (and possibly the valve actuator of the RSS) will be maintained according to normal plant schedules. All components requiring maintenance are situated above the reactor dome for easy access. Provision is made to replace a subsystem, if required.

2.4.2.3 Control channel blockage

The design requirement of core internals is that there can be no possible disturbance, including seismic, which could lead to a misalignment of the reflector blocks, or any other damage which can result in the control rods or SAS not being able to be inserted.

Item Number	Document Number	Title		Quantity
1	RCSS-17000	R08 DRIVE HOUSING		18
2	RCSS-16000	R08 CRDM HOUSING		18
3	RCSS-16100	R08 DRIVE HOUSING ATTACHMENT BOLT	M24 x 80	18
4*	RCSS-11000	R05 CRDM SHORT ASSEMBLY		9
5	RCSS-14000	R05 CONTROL ROD GUIDE TUBE ASSEMBLY		9
6	RCSS-13000	R05 SECONDARY SHOCK ABSORBER ASSEMBLY		18
7*	RCSS-15000	R05 DRIVE ASSEMBLY		18
8*	RCSS-15170	R08 CRDM MOTORT ATTACHMENT BOLT	M14 x 40	18
8*	RCSS-12000	R08 CRDM LONG ASSEMBLY		9

Figure 8: GENERAL LAYOUT DRAWING – REACTIVITY CONTROL SYSTEM

Figure 9: GENERAL LAYOUT DRAWING – RESERVE SHUTDOWN SYSTEM

3.   FUEL

3.1   Summary

The PBMR core is designed around the Low Enriched Uranium (LEU) – TRISO fuel element developed for HTR in Germany from 1969 to 1988. The German design is supported by a large database consisting of test data from irradiation tests in Materials Testing Reactors, and data obtained from a large number of tests on fuel elements in the AVR under operating conditions.

The first pebble bed fuel elements of German design produced on a large scale were loaded into the AVR in 1968. Development of fuel elements continued and culminated in proof tests performed in 1989 on fuel elements using LEU Tri-coated Isotropic (TRISO) coated particles. The fuel elements for the PBMR are equivalent to German fuel elements based on LEU-TRISO coated particles.

The properties of LEU-TRISO coated particles are among the most important factors in determining the radiological safety of any operating pebble bed reactor. Thus, the fission product retention in the fuel elements, as well as the maximum fuel temperature that can be tolerated in the reactor core, will be determined by the coated particle properties of the fuel.

3.2   Fuel Elements (Spheres)

3.2.1   Fuel kernel

The spherical fuel kernel consists of stoichiometric uranium dioxide. Four layers or coatings surround each kernel. Proceeding outwards from the fuel kernel they are the Buffer Layer, the Inner Pyrocarbon Layer, the Silicon Carbide Layer, and the Outer Pyrocarbon Layer.

3.2.1.1 Buffer layer

The purpose of the buffer layer is to provide void volume for gaseous fission products, in order to limit the pressure build-up within the coated particle. As a result of its porosity, the buffer layer also serves to decouple the fuel kernel, which swells with increasing burn-up of fuel, from the high-density layers which are important in containing fission products within the coated particle.

3.2.1.2 Inner pyrocarbon layer

The inner high-density, isotropic layer of pyrolytic carbon, also referred to as the Inner Low Temperature Isotropic (ILTI) layer, forms the first pressure barrier against fission products pressure within the fuel kernel, thereby reducing the pressure on the next layer (SiC) which has limited

tensile strength. Although an intact ILTI layer forms a practically impenetrable barrier for fission gases and fission products iodine, it becomes increasingly pervious to cesium and strontium at higher temperatures.

3.2.1.3 Silicon carbide layer

The silicon carbide layer retains gaseous and other fission products. It also acts as the primary pressure vessel boundary within a coated particle. The production of fuel elements having coated particles with intact SiC layers, and the guarantee that these layers will remain intact under all foreseeable reactor core conditions, form the basis for safe operation of the PBMR.

3.2.1.4 Outer pyrocarbon layer

The Outer Low Temperature Isotropic (OLTI) pyrolitic carbon layer protects the SiC layer against damage in the fuel manufacturing process following the coating process. It also provides prestress on the outside of the SiC layer, due to shrinkage of the OLTI layer under fast neutron irradiation during the fuel lifetime in the reactor core, thereby reducing the tensile stress in the SiC layer.

3.2.2 Fuel element matrix

Coated particles are embedded in graphite matrix material consisting of a mixture of natural graphite and electrographite, together with a phenolic resin as a binder material. Highly graphitized materials are used for fuel manufacture to ensure dimensional stability during irradiation with fast neutrons. Highly graphitized material also has the desirable property that it can be pressed to the required density, relatively easily.

3.2.3 Fuel-free zone

A fuel-free zone of 5 mm, consisting of the same matrix material used for the inner zone, surrounds the inner fuel-containing zone of each fuel element. The purpose of this zone is to protect the inner zone from mechanical and chemical damage during handling and operation.

3.3 Fuel Operation

In order to have a self-sustaining or 'chain' reaction, the PBMR pebbles contain uranium enriched to approximately 8% in U-235. U-235 is the isotope of uranium that undergoes fission reactions in the core. The U-235 isotope occurs in natural uranium in a concentration of 0.7%.
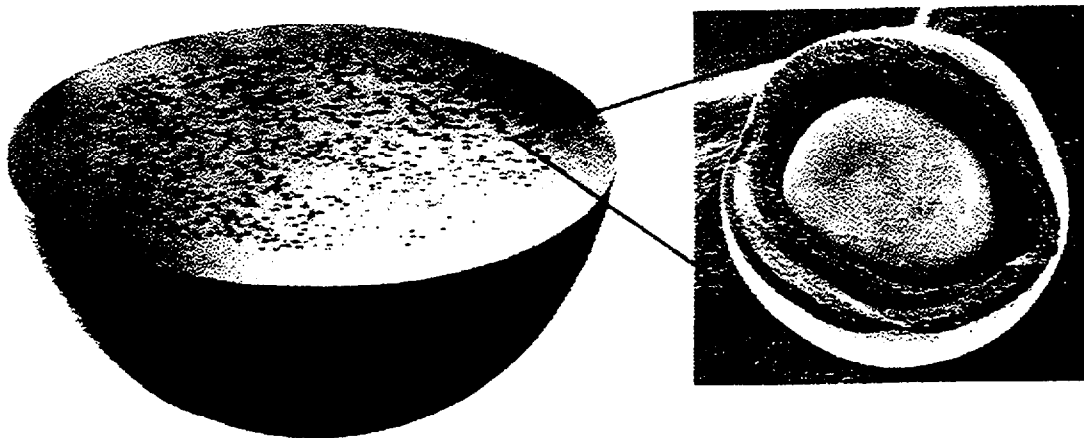
Figure 10: CUT-AWAY OF FUEL SPHERES

The reactor is continuously replenished with fresh or reusable fuel from the top of the reactor, while the used fuel is removed from the bottom. The fuel pebbles are measured to determine the amount of fissionable material that is left in them after each cycle through the reactor core. If the pebble still contains a usable amount of the fissile material, it is returned to the reactor at the top for a further cycle. Each cycle lasts approximately three months.

When a fuel sphere has reached a burn-up of 80 000 Megawatt Days per Tonne (MWd/T) of uranium metal, it is removed and sent to the spent fuel storage facility. Each fuel pebble passes through the reactor approximately 10 times and a reactor will use 10 to 15 total fuel loads in its design lifetime. A fuel sphere will last approximately three years, and a graphite sphere approximately six to 30 years, depending on the type of graphite used.

The extent to which the enriched uranium is used to depletion (called the extent of 'burn-up') is much greater in the PBMR than in conventional power reactors. There is therefore minimal fissile material that could be extracted from depleted PBMR fuel. This, coupled with the level of technology and cost required to break down the barriers surrounding the spent fuel particles, protects the PBMR fuel against the possibility of nuclear proliferation or any other covert use.

3.4   Fuel Performance

This safe confinement of radioactivity is assured by the design of the fuel particle coatings. The silicon carbide layer, in particular, is so dense that up to temperatures of 1 650 °C, no radiologically significant quantities of gaseous or metallic fission products are released from the fuel elements. The core temperature response during a DLOFC event does not exceed this temperature. It is important to note that the natural heat removal exceeds the decay heat generated within a short time.
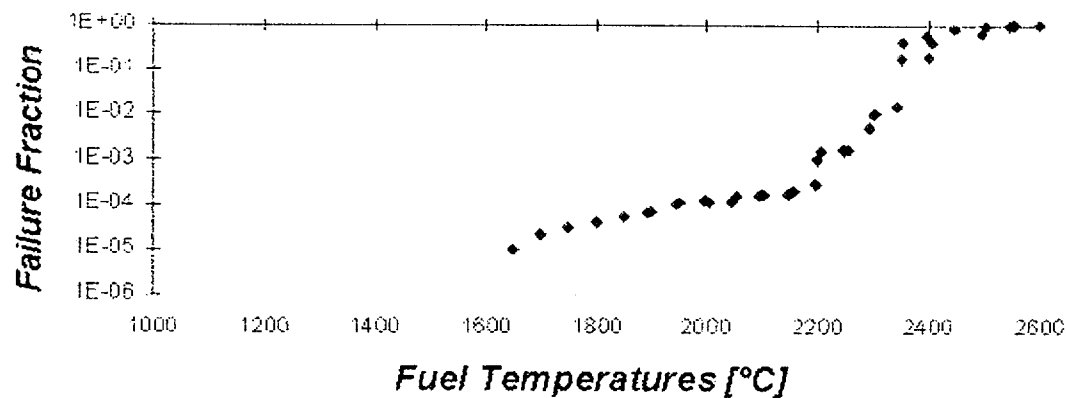
Figure 11: FUEL FAILURE vs FUEL TEMPERATURE

4.   THERMODYNAMICS

4.1   Brayton Cycle

The thermal energy is extracted from the core and transferred to the PCU by means of a circulating pressurized helium gas stream. This thermal energy is converted into electrical energy in the PCU, utilizing a Brayton cycle thermodynamic process. For the PBMR, the Brayton cycle will consist of a two-stage intercooled compression and recuperated process.

The ideal Brayton cycle consists of two isentropic and two isobaric processes as shown in **Figure 12**. Starting at 1, gas at a low pressure and temperature is compressed in an isentropic process to a higher pressure and temperature (2). From 2 to 3, the gas is heated in an isobaric (constant pressure) process to the maximum cycle temperature. From 3 to 4, the hot high-pressure gas is expanded isentropically in a turbine to a lower pressure and temperature. The cycle is completed from 4 to 1 by cooling the gas at constant pressure.
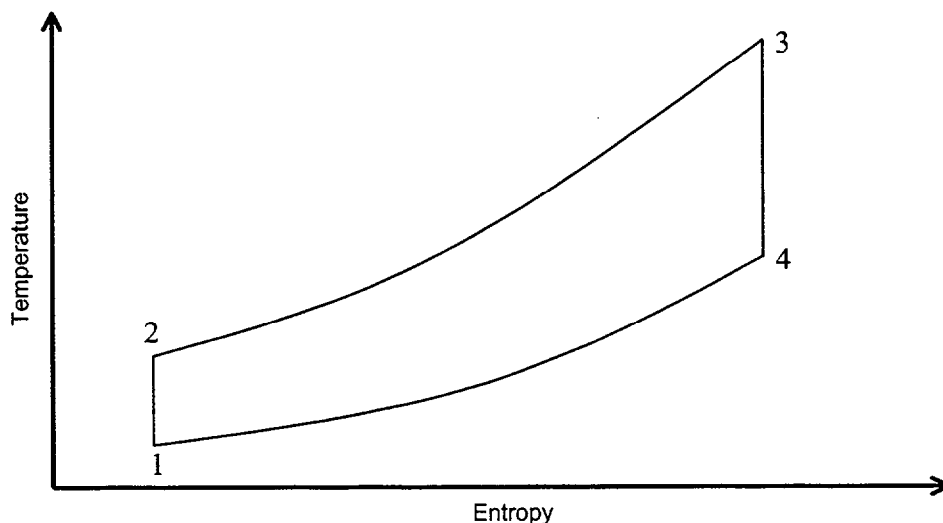
Figure 12: THE IDEAL BRAYTON CYCLE

The efficiency of the ideal Brayton cycle can be improved by using a portion of the heat rejected during the cooling process (4 to 1) to preheat the gas before it enters the heater. Another method of improving the efficiency is to use multistage compression with intercooling. The PBMR utilizes both these mechanisms, and the modified cycle on which the PBMR is based is referred to as the recuperative Brayton cycle. Another distinctive characteristic of this recuperative Brayton cycle is the use of helium as the working fluid. A schematic layout of the plant to perform this cycle is shown in **Figure 13**, while the temperature-entropy diagram of the cycle is shown in **Figure 14**.

Starting at 1, helium at a relatively low pressure and temperature (1) is compressed by an LPC to an intermediate pressure (2), after which it is cooled in an intercooler to state 3. An HPC then compresses the helium to state 4. From 4 to 5, the helium is preheated in the recuperator before entering the reactor, which heats the helium to state 6. After the reactor, the hot high-pressure helium is expanded in a High Pressure (HP) turbine to state 7, after which it is further expanded in an LP turbine to state 8. The HP turbine drives the HPC while the LP turbine drives the LPC. After the LP turbine, the helium is further expanded in the PT to pressure 9, which is approximately the same as the pressure at 10 and 1. From 9 to 10, the still hot helium is cooled in the recuperator, after which it is further cooled in the pre-cooler to state 1. This completes the cycle. The heat rejected from 9 to 10 is equal to the heat transferred to the helium from 4 to 5.

Figure 16 is typical of a temperature/specific entropy diagram for the PBMR Recuperative Brayton cycle at 100% Maximum Continuous Rating (MCR). The specific entropy is referenced to $T_0 = 0$ °C and $P_0 = 10$ MPa.
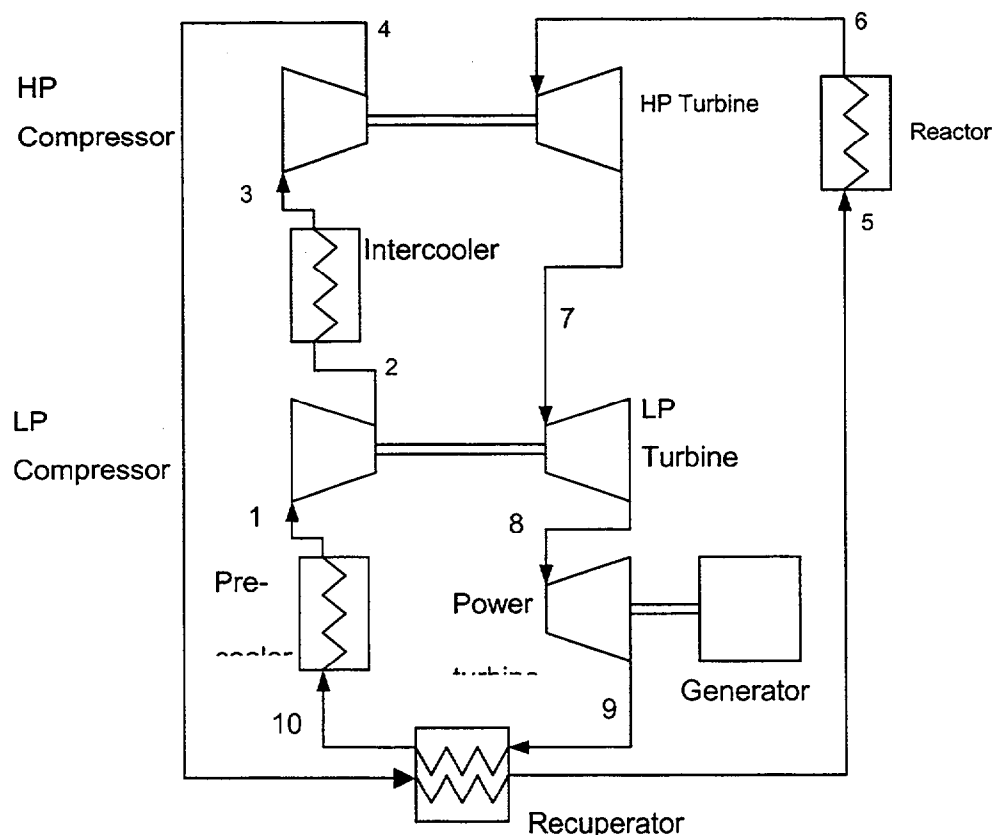
Figure 13: SCHEMATIC PLANT LAYOUT OF THE PBMR RECUPERATIVE BRAYTON CYCLE
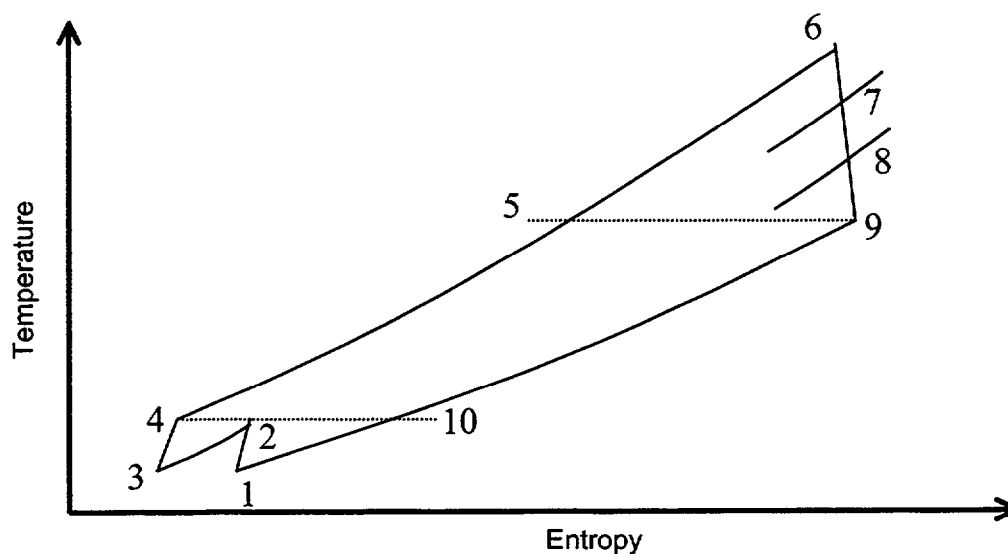
Figure 14: TEMPERATURE-ENTROPY DIAGRAM OF THE PBMR RECUPERATIVE BRAYTON CYCLE
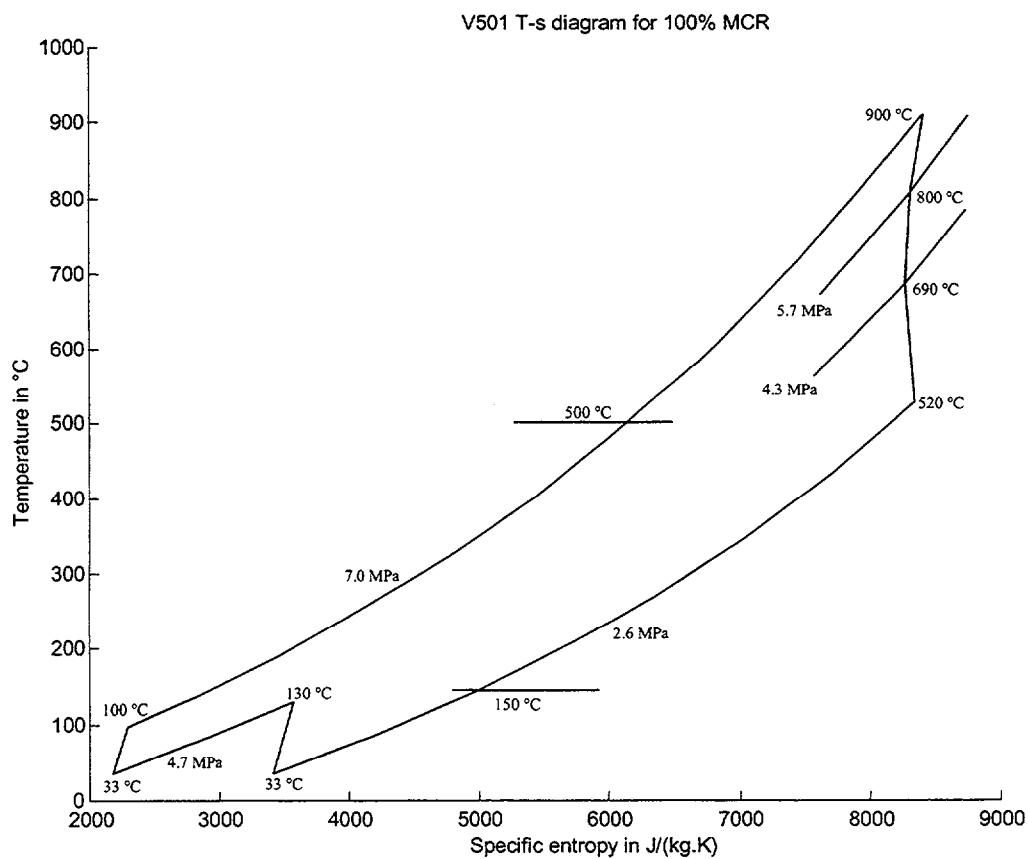
Figure 15: TEMPERATURE-ENTROPY DIAGRAM FOR 100% MCR

Figure 16: SCHEMATIC REPRESENTATION OF HELIUM GAS FLOW PATHS THROUGH MPS

5.   POWER CONVERSION UNIT

5.1   Introduction

The MPS of the PBMR consists of two main parts. These are the RU, where thermal energy is generated by a nuclear reaction, and the PCU, where the thermal energy is converted to mechanical work and then to electrical energy by means of a thermodynamic cycle and a generator. This section describes the PCU and provides an overview of its operation.

The PCU converts heat as received from the reactor, to electrical energy. Waste heat of the Brayton cycle is rejected by internal heat exchange to the active heat removal system. The PCU is designed to deliver 110 MW nominal electrical energy to the grid.

5.2   Major Features and Components

The PCU is comprised of the following:

- A manifold, containing:

    - High-pressure Turbo-unit (HPTU), vertically mounted.

    - Low-pressure Turbo-unit (LPTU), vertically mounted.

- Power Turbine with Generator (PTG), vertically mounted on the end of the manifold, below which is the:

    - Recuperator.

    - Pipe and valve system.

- Pre-cooler.

- Intercooler.

5.2.1   Turbo-units

The function of the turbo-units is to provide the pressure in the cycle to drive the system turbines. Power to do this is supplied by an integral turbine.

The turbo-units are inserted into fixed vertical barrels inside the manifold.

The design of the HPTU and LPTU is based on existing technology available from gas turbine suppliers, particularly in the areas of design methodology, performance, materials and fabrication methods. Both turbo-units are very similar in design. Complex inlet and outlet volutes have been abandoned in favour of simple dump diffusers. Both machines utilize electromagnetic and catcher bearings of known sizes. Inlet temperatures as well as rotational speeds are well within those

employed by modern gas turbine designs. Adjustable compressor blades (±15° angle) are required for controllability of the plant. Compressor temperatures are below 100 °C. No blade control has been designed into the turbines.

5.2.2   Power turbine generator

The function of the PT is to absorb the energy in the high-pressure and high-temperature helium stream via the PT, and supply the power to the high voltage electrical network via the Generator System.

The PTG forms part of the active control of the recuperated Brayton cycle, in conjunction with HPTU/LPTU, bypass valve and HICS.

The design of the PTG is based on the following technologies:

- The PT design is based on existing PT technology, particularly in the areas of design methodology, performance, materials and fabrication methods.

- The electrical generator design is based on conventional generator technology to the maximum extent possible, recognizing two major differences, namely vertical orientation and operation in a helium environment. The major reason for having a submerged generator is that it obviates having a shaft penetrating the PPB. The reason for the vertical orientation is the limitation on the size of the radial electromagnetic bearings to compensate for the imbalance of gravity forces.

- The design of the Electromagnetic Bearings (EMB) is based on existing EMB technologies.

- The EMB sealing system is based on the axial EMB design concept for the PT. Although this system is not critical to the operation of the plant, it is important to the efficiency of the plant, and therefore its operating economics. Roughly 8 to 10 MWe will be lost if this sealing system does not perform as designed.

5.2.3   Recuperator

The function of the recuperator is to return heat downstream of the PT back to the flow path ahead of the reactor. This raises the helium temperature to the reactor. The high temperature return helium is kept away from any PB component by forcing the helium through well-insulated pipes to the ceramic core structures.

5.2.4 Cycle heat exchangers (pre-cooler and intercooler)

The cycle has two heat exchangers:

- The pre-cooler located downstream of the recuperator.

- The intercooler located between the two compressors.

With the closed loop Brayton cycle, the pre-cooler anchors the temperature of the low-pressure line. The intercooler reduces the volume flow to the second compressor, causing a reduction of compressive work.

The gas/water pre-cooler and intercooler heat exchangers are fairly standard heat exchanger designs. These heat exchangers are tube-finned type with very compact fin spacing. The gas pressure side is always at a higher pressure than the waterside, in order to be able to detect
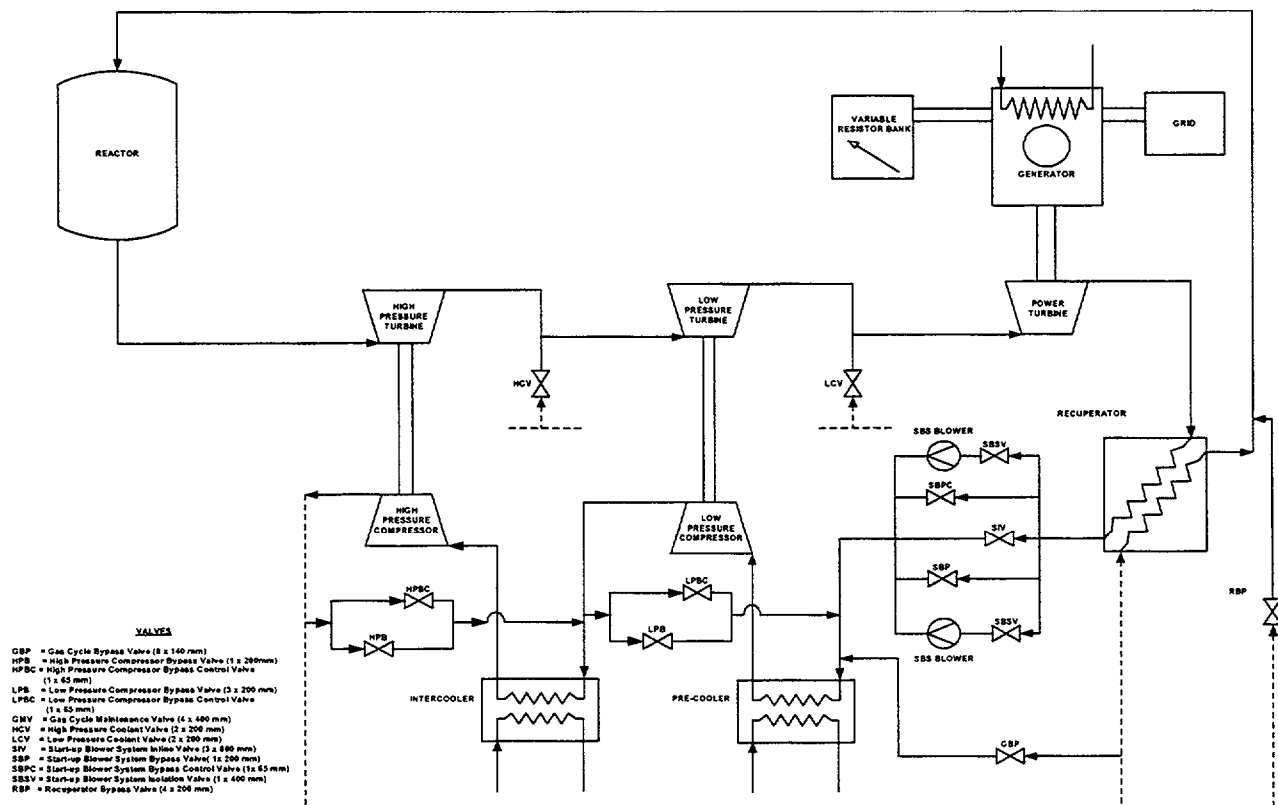
helium in the water circuit.

Figure 17: SCHEMATIC OF PBMR PLANT CYCLE SHOWING THE MPS COMPONENTS

6.   MAJOR DESIGN FEATURES AND AUXILIARY SYSTEMS

6.1   Pressure Boundary System

The PPB of the PBMR consists of the following systems:

- the Vessel System;

- the Vessel Support System; and

- the Pressure Relief System.

6.1.1   Vessel system

The Vessel System is divided into two subsystems, namely the Reactor Pressure Vessel (RPV) and the PCUPV.

The pressure boundary system contains the helium coolant by maintaining the boundary integrity. It also provides structural support and alignment for the components that are housed within the RPV and the PCUPV.

The RPV internal volume is separated from the internal volume of the PCUPV by means of a separation structure. This separation is necessary to maintain the RPV wall at a temperature different to that of the Manifold Vessel of the PCUPV. These two vessels are pressure connected, and no differential pressure exists across this separation structure.

During normal operation, the RPV wall temperature is maintained at between 280 °C and 300 °C by means of a combination of the heat transfer design of the core structures, the RPVCS and the RCCS.

The Manifold Vessel of the PCUPV is cooled from the inside by the helium stream leaving the HPTC. The maximum wall temperature will be maintained during normal operation at approximately 85 °C to 120 °C.

The generator internal coolers maintain the Generator Vessel wall temperatures at approximately 80 °C.

The internal walls of the Pre-cooler Vessel and the Intercooler Vessel are in contact with the pre-cooler and intercooler outlet flows respectively, and their temperatures will therefore be maintained at less then 30 °C during normal operation. The Recuperator Vessel will be maintained at a temperature of 350 °C.

The RPV and certain parts of the PCUPV are cooled from the inside by the helium stream leaving the HPTC. During normal operation, the maximum wall temperature will be maintained at approximately 105 °C to 120 °C.

Figure 18: PRIMARY PRESSURE BOUNDARY
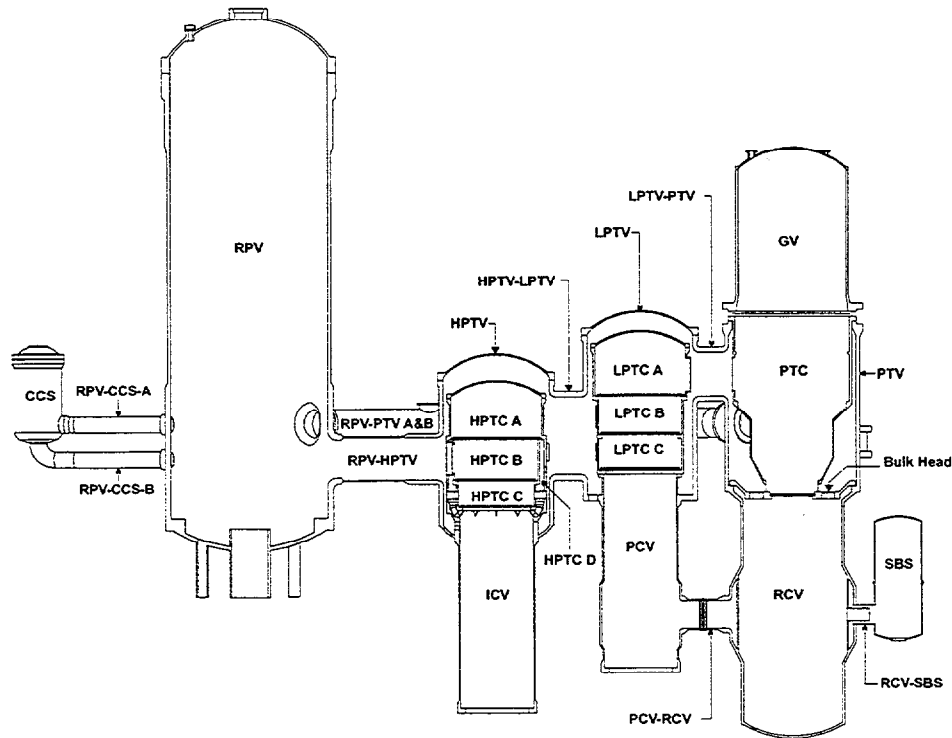
Figure 19: MAIN POWER SYSTEM SCHEMATIC

6.1.2 Vessel support system

The principle used for supporting the PPB system is to restrain all degrees of freedom of the intersection point of the RPV centreline. Unrestrained thermal expansion is allowed as follows:

- PCUPV centerline – horizontally along its centerline;

- RPV – in the radial and axial (vertical) direction; and

- PCUPV – horizontally along its centreline

6.1.3 Pressure relief system

Overpressurization protection is provided for the PPB. This system protects the PPB against overpressurization by initiating a release of helium through a Blowdown System, and by initiating a PCU trip. The first results in a reduction of the helium inventory, and the second immediately eliminates the only means of pressure increase in the system.

6.2   Helium Inventory Control System

The Helium Inventory Control System (HICS) is made up of a number of subsystems:

- Inventory Control System (ICS);

- Helium Purification System (HPS); and

- Helium make-up System (HMS).

The HICS is described in **Section 2** of this document.

6.3   Auxiliary Systems

6.3.1   Active cooling system

The Active Cooling System (ACS) has specifically designed, controlled components to cool the required higher level systems or components. Cooling towers are provided to act as a back-up to selected auxiliary systems.

The function of the ACS is to remove waste heat from the PCU and from the following auxiliary subsystems:

- Heating, Ventilation and Air-conditioning System.

- Compressed Air System.

- Primary Loop Initial Clean-up System.

- Fuel Handling and Storage System.

- Helium Inventory Control System.

- Start-up Blower System.

- Reserve Shutdown System.

- Core Conditioning System.

- Reactor Pressure Vessel Conditioning System.

The ACS is designed to operate unattended. Starting sequences, selection of plant, and pump changeovers are fully automated.

The ACS is made up of two main sections, viz. a site-specific section hereafter called the Ultimate Heat Sink System (UHSS), linking the ultimate heat sink to the module building, and a generic section comprising all the circuits housed within the module building, which will remain essentially the same irrespective of where the module is constructed, or whether the site consists of one module or multiple modules. The site-specific section can be designed to dissipate waste heat via

an open or closed water circuit to any convenient source, be it the sea, a river, a dam, etc., or to the atmosphere by means of cooling towers.

Generic Design Section: Module Building	Site Specific Section: Ultimate Heat Sink System
- Main closed circuit - Auxiliary closed circuit - Reactor cavity cooling system - Back-up cooling towers	- Pumping and filtration - Cooling towers, etc.

All closed circuits contain demineralized water to which an inhibitor has been added to prevent the formation of scale or rust. This is particularly important in the case of the RCCS, where foreign particles can become activated.

The main cooling system, the auxiliary cooling system, and the RCCS are all connected directly to the UHSS by means of their respective heat exchangers. In two instances, however, i.e. the generator cooling system and the core conditioning cooling system, a smaller buffer circuit is installed between the heat source and the UHSS. The reason for the small buffer circuits is to limit the volume of water which can enter the reactor in the event of a rupture of the water-gas heat exchangers.

6.3.2　Reactor cavity cooling system

The RCCS removes heat from the reactor cavity during all modes of reactor operation. This system is described in **paragraph 2.3** of this document.

6.3.3　Used fuel cooling system

During maintenance or other outages of the reactor, fuel is transferred to a used fuel storage vessel. The function of the Used Fuel Cooling System (UFCS) is to remove the decay heat from this vessel. The fuel temperature is maintained at a safe storage level for fuel in a helium environment.

The annular vessel containing the used fuel is positioned in a water-filled tank through which cooling water is circulated. The structure is connected in parallel with the three RCCS trains, allowing the UFCS cooling water to be pumped through any of the RCCS heat exchangers. If fault conditions, such as loss of electrical power, occur while fuel is in the used fuel vessel, the system will automatically change to passive operating mode in the same way as the RCCS, and the water in the tank will heat up and, if necessary, boil off, thereby maintaining the integrity of the fuel until

repairs can be done. Water from an external source can also be pumped into the UFCS to replace water lost by evaporation.

6.3.4   Heating ventilating and air conditioning system

The Heating, Ventilation and Air-conditioning (HVAC) System is designed to do the following:

- supply fresh air to the building;

- maintain specified environmental parameters, temperature and (where required) humidity;

- maintain sub-atmospheric pressure and direction of flow in the controlled zone;

- maintain positive pressure in the control rooms;

- remove heat from mechanical and electrical equipment;

- remove heat from the Spent Fuel storage area;

- remove airborne radioactive gases, aerosols and dust particles by purging and filtering;

- minimize environmental impact by filtering exhaust air; and

- minimize internal building contamination by filtering recirculated air.

Each module's HVAC system consists of the following:

- One common outside air supply to the red and green zones' air handling units.

- One common air handling system for the various areas of the red zone, including 100% standby facility on fans, cooling coils and control valves, operating in two modes: operating with no access, and operating when access is granted.

- One common air handling system for the various areas of the green zone, including 50% standby facility on fans, cooling coils and control valves, operating in continuous mode.

- One common extract air system from the various areas of the red zone.

- One dedicated exhaust (purging) air system controlling negative pressure in the reactor cavity.

- One extract air system from the Spent Fuel area.

- One common extract air system from the various areas of the green zone.

- One common exhaust air system from the various areas of the controlled zone.

- The air distribution system consisting of concrete building shafts and steel ducts, airflow control dampers, and air inlet and outlet points.

- The extract and/or recirculation air HEPA filters installed in the airtight casings.

- The two-stage exhaust air filters with iodine adsorption and HEPA filters installed in the airtight casings.

- Two independent fresh air intakes, one for the white zone and another for controlled (green and red) zones.

- Two common air handling systems, one for the green zone, one for red zone, including standby facility on fans, cooling coils, control valves.

- Two common air-handling systems for the white zones, including standby facility on fans, cooling coils and control valves.

- Common to all zones, the central chilled water system. The central cooling system consists of water chillers, pumps and chilled water distribution piping. The chiller's heat is removed by the ACS.

- Common to all zones, the Control System. The air handling units are both controlled from a centralized monitoring and control system situated in the Power Plant Services Building (PPSB), and the localized module control system.

The HVAC's Control and Instrumentation System (CIS) is able to control and monitor start/stop functions, reset local control set points, and monitor the safe and efficient functioning of all HVAC equipment. Zone static pressures are also monitored.

6.3.5   Airlocks

The Airlock System design is based on the following functional requirements:

- a barrier between zones of different radiation level and classification, i.e. red to green zones, green to white and white to ambient;

- a barrier between zones of different pressures as maintained by the HVAC system;

- a protective barrier to contain the over-pressure derived from a helium leak depressurization event;

- a protective barrier to contain the over-pressure derived from an external pressure wave; and

- a secondary barrier to contain radioactive emissions.

Four different types of doors shall be used for the airlocks, namely:

- Type 1:   Standard panel construction door.

- Type 2:   Door rated for depressurization event and to provide primary radiation shielding.

- Type 3:   Door rated for over-pressure from an external pressure wave.

- Type 4:   Door rated for high-pressure depressurization event and to provide primary radiation shielding.

The doors will mostly be swing doors with vertical hinges, although sliding door/s with floor rails and horizontal hatches with hinges on one side will also be used.

Airlocks rated for depressurization events or for external pressure waves have the same classification as the module building. The remaining Airlocks are not classified as safety systems.

6.3.6   Primary loop initial clean-up system

The Primary Loop Initial Clean-up System (PLICS) consists of the following two subsystems:

- the PLICS vacuum subsystem; and

- the PLICS heater subsystem.

The function of the PLICS is to remove water, air and other gases from the primary loop before initial commissioning of the MPS. The PLICS will also be used before commissioning of the MPS after maintenance operations.

The core structures and pebbles will be heated to a temperature between 250 °C and 300 °C, using the PLICS heater subsystem to increase the rate at which water is desorbed from it. The system will then be flushed with nitrogen or dry air to remove the desorbed water.

After this operation, the primary loop will be evacuated, using the PLICS vacuum subsystem. The gases and vapours shall be filtered for dust and scrubbed by the activated carbon filters of the PLICS vacuum subsystem before they are released to atmosphere.

The PLICS system will be contaminated with dust-borne radioactivity when used to evacuate the MPS after maintenance operation on the MPS. The design and construction of the PLICS shall facilitate the decontamination of contaminated parts. Other parts, which cannot be decontaminated, shall be designed for easy removal and replacement.

6.3.7   Compressed air system

The bases of the Compressed Air System (CAS) design are:

- Automatic operation.

- Adherence to ANSI/ASME standards.

- Adherence to statutory safety requirements.

- No contaminated releases to the environment.

- Reliability of supply by means of redundant components.

- Low noise pollution.

- Standardization of components and fittings between compressor stations to allow for interchangeability and ease of maintenance.

Two compressed air stations are provided, each station consisting of electrically-driven compressors with air dryers, air receivers, silencers, switchgear, coolers, filters and controls. Station 1 consists of three high-pressure compressors, two operational and one standby, while Station 2 consists of two low-pressure compressors without standby capacity. Oil-free air is supplied at controlled pressures to workshops and machine rooms for maintenance purposes, to the cooling water systems for maintaining pre-set pressures in these systems, and to pneumatic valve actuators. CAS operate automatically when enabled from the Module Automation System and from the Nuclear Power Plant (NPP) Automation System.

Compressed air for the pressurization of the cooling water systems is continuously available. All other supplies are automatically isolated at the receiver connection by means of normally closed spring operated valves. For the services building, an alternative supply connected to a portable compressor and dryer, is provided from outside the building in case of the failure of the fixed set.

Air dryers are of the desiccant type with after-coolers and separators, and are skid mounted. Distribution pipework and fittings are of steel, and routed in accordance with building requirements.

6.3.8   Pressure relief system

The function of the system is to ensure that an over pressure in the building, caused by a depressurization event, is relieved by releasing the helium to atmosphere. The system will close after the event to enable normal HVAC operation to be reinstated.

The system consists of a Standard Relief Route for smaller breaks and an Emergency Relief Route for the bigger breaks.

6.3.8.1 Standard relief route for smaller breaks

The function of the standard pressure relief route is to vent pressure build-up in certain areas due to smaller high-pressure pipe breaks to the atmosphere outside of the module building. Depressurization should be rapid enough so that the maximum build-up does not exceed 35 kPa gauge pressure.

To achieve rapid venting, the Rupture Panel vents directly into a dedicated vertical Pressure Relief Stack on the side of the building, serving as a common area for all cavities. Certain cavities are not

located adjacent to this stack, but are connected via dedicated Pressure Relief Ducts, which traverse neighboring cavities. The ducts are designed to withstand the pressure differential criterion of 35 kPa internally and externally.

Rupture Panels are designed to rupture at a set overpressure (gauge pressure) of 10 kPa. The setting is the optimal value and was obtained from parametric sensitivity analyses of the pressure regime in cavities and the Pressure Relief Stack, taking into account cavity volume, rupture panel size, duct size and route, stack size, and the relative location of all feeding rupture panels/ducts into the Pressure Relief Stack.

Once a relief route has been activated by a break event, a pressure pulse translates into the Pressure Relief Stack. Other relief routes connected along its height will not be opened inadvertently, either by the pulse, or by the positive or negative phase of the pulse, due to the design settings of the Rupture Panels.

The Pressure Relief Stack exhausts to the outside atmosphere through a damper, which is normally open. The damper closes automatically after passage of the blast pulse, in order to protect against ingress of debris and dust following the negative suction phase of the pulse. In addition, the orifice of the Pressure Relief Stack is protected by a light-construction blow-off dust cover, thus protecting the Pressure Relief Stack against natural elements and dust.

6.3.8.2 Emergency relief route

The emergency routes are designed to relieve pressure build-up due to extreme, large pipe breaks, exceeding 50 kPa gauge pressure. The routes are designed on a cascading basis, i.e. when a break occurs in a certain cavity (for example in the fuel handling area), a Rupture Panel vents in to the neighbouring cavity at 10 kPa, which again vents into a neighboring cavity if the pressure exceeds 10 kPa. The route leads to the uppermost level under the roof, from where excess pressure is discharged through vent structures to the atmosphere. Dedicated relief ducts and routes are not provided for the emergency breaks because of the very low probability of occurrence. Under such conditions, the undamaged integrity of only the citadel structure is a requirement.

6.3.9 Decontamination system

The Decontamination System (DS) is required to treat contaminated items or components from the plant to reduce the level of contamination of the item to a level that allows for its disposal or maintenance.

The two types of contamination to be considered are:

- non-fixed, i.e. dust-borne; and

- fixed, i.e. plate out.

The requirement for the decontamination equipment focuses on minimizing worker radiation exposure, volume of radioactive waste generated by the decontamination activities, and time taken for decontamination utilizing the ALARA principle for exposure to radiation.

The DS will consist of various units, depending on:

- the size and weight of the component; the type of contamination;

- the method of decontamination to be used;

- the initial level of activity and the level to which this has to be reduced; and

- the purpose for which the component is being decontaminated, i.e. rework or disposal.

Decontamination methods/processes to be considered are as follows:

- detergent and hot water as a hand-wipe operation;

- vacuum cleaning;

- chemical cleaning;

- solvent cleaning, in a self-contained unit;

- abrasive blasting in a self-contained unit; and

- ultrasonic cleaning.

6.3.10   Waste handling system

The Waste Handling System (WHS) consists of the following two subsystems:

- Liquid Waste Handling Subsystem; and

- Solid Waste Handling Subsystem.

The function of the system is to handle and store low-level, liquid and solid, radioactive waste generated during normal operation, maintenance activities, and upset conditions of the PBMR. No provision will be made for the handling of gaseous radioactive waste, since the activity levels and quantities of waste are expected to be low enough to be discharged to the atmosphere after being filtered by the HVAC system.

The only high-level radioactive waste produced by the plant is spent fuel and damaged fuel pebbles that will be contained in containers of the FHSS inside the module building.

6.3.10.1 Liquid waste handling subsystem

Liquid waste generated during the operational activities of the PBMR shall be collected in central tanks where it will be monitored and/or processed before discharged to the environment. The liquid waste will be a variable mixture of chemicals, possibly containing solvents, suspended solids and abrasive blast residue.

The processing of the waste will be on a batch basis. A control/monitoring system will therefore be incorporated in the system to ensure that waste of unacceptable radiation dose cannot be discharged. Prior to sampling and analysis, the tank contents will be mixed to ensure that the measurement taken is representative of the tank contents.

The level of radioactivity, radioactive nuclide content and chemical composition of the liquid will be measured and chemically treated in order to render it suitable for discharge.

The liquid WHS shall be designed to process liquid waste from wherever it is generated, with the objective of compliance with the necessary discharge authorization. A batch of liquid effluent shall be sampled prior to discharge. Refer to **Table 1** for anticipated quantities of liquid waste generated by a PBMR module.

Table 1: ANTICIPATED QUANTITIES OF LIQUID WASTE GENERATED BY A PBMR MODULE

ACTIVE WASTE				
Description	**Average Quantity (m^3/d)**	**Maximum Quantity (m^3/d)**	**Average Quantity (m^3/a)**	**Specific Activity (Bq/m^3)**
Liquid waste from decontamination facility and laboratory	1	3	480	Up to 6×10^7
Liquid waste from laundry	1	4	500	Up to 6×10^7
POSSIBLY ACTIVE WASTE				
Description	**Average Quantity (m^3/d)**	**Maximum Quantity (m^3/d)**	**Average Quantity (m^3/a)**	**Specific Activity (Bq/m^3)**
Liquid waste from building floor drain sumps (HICS, PLICS, HVAC)	0.4	4.1	365	Up to 6×10^6
Liquid waste from showers and washrooms	0.23	0.54	100	Up to 6×10^6

6.3.10.2 Solid waste handling subsystem

The design of the system shall provide for the following:

- Classification of materials in terms of level of radioactivity of contaminated materials.

- Sorting of material prior to packing in drums.

- Compacting press, for compaction of waste into steel drums.

- Filling, compacting, and sealing steel drums with low-level waste.

- Equipment required for handling waste during the filling, compacting and sealing process.

- Equipment required for moving the drums from their filling position to the storage area.

The anticipated average annual quantity of solid waste produced by a single module is approximately 10 m^3 (50 x 0.2 m^3 steel drums) of compacted waste at an overall compaction ratio of approximately 5:1. The steel drums accumulated over a period of three years, shall be stored in the Low-level Waste Store. Refer to **Table 2** for the anticipated quantities of solid waste produced by a PBMR module.

Table 2: ANTICIPATED QUANTITIES OF SOLID WASTE PRODUCED BY A PBMR MODULE

Description	Number of Drums per Annum
Solid operational waste	25 to 100
Filters	8
Unserviceable activated and contaminated SSC	3

6.3.11   Fire protection system

The general philosophy of the FPS is that in the event of a fire within a fire detection surveillance zone, the fire detection and alarm system will clearly activate an audio-visual alarm at a fire suppression controller and/or unit fire alarm panel. The fire alarm panel will repeat this alarm via a fibre optic network to the main fire alarm panel which is located in the station services building. Annunciation and display are primarily presented at the operator console, including graphic layouts and operator interaction facilities provided by means of a visual display unit and dedicated operator's keyboard.

The fire detection and alarm system will:

- alert personnel as to the location of the fire;

- advise personnel as to the condition of the detection system;

- automatically initiate fire suppression systems;

- provide executive outputs to initiate other plant trips or control; and

- aid fire-fighting personnel by highlighting the area affected by the fire.

The FPS consists of four distinct subsystems. These are as follows:

- A fire detection system in the module and services building for early warning purposes. The detection system interfaces with mechanical fixed fire protection systems for alarm activation.

- Fixed active fire protection systems which consist of an activated water spray system for suppression of oil fire risks, and an automatic activated gaseous spray for switchgear, etc.

- Hydrants, hose reel and portable extinguishing equipment positioned in the buildings for manual fire-fighting purposes. Hydrants and hoses will also be provided for the contractor's yards.

- Passive measures against the spread of fires, i.e. by sealing openings in floors and walls. Fire doors will be provided as necessary.

The detection system will be sited to provide early warning of fire conditions in all risk areas. This system will be interlocked with the HVAC system to automatically shut the dampers on supply and extract air routes. The Fire Detection and Alarm System (FDAS), which comprises an integrated system for fire detection, control, interlocking, communications, and supervisory functions including annunciation and data logging, is suitable for power station environments, and has a proven track record in terms of reliability. The FDAS is designed for continuous 24 h automatic operation covering the module and services building.

Annunciation and Display is primarily presented at the Operator Console. This includes graphic layouts and operator interaction facilities provided by means of a Video Display Unit (VDU) and dedicated operator keyboard.

Two independent water reservoirs are provided for the FPS, each holding at least enough water for two hours' full operation of the system. Three ring mains are provided, the first around the module building, the second around the services and auxiliary buildings, and the third around the temporary contractor's yards. From the reservoirs, water is pumped into these ring mains, and from there, into the respective buildings. At least two risers are provided in each building.

The reservoirs will be filled from the municipal supply line.

Portable equipment and safety gear such as face protection, tunics and extinguishers will be sited in and around the facility at accessible points.

The passive protection, such as fire seals, will coincide with dampers on the HVAC system on a sector base similar to that of Koeberg Power Station. Other passive measures such as fire doors, fire escapes and emergency lighting will be provided.

6.3.12 Equipment handling system

The Equipment Handling System (EHS) will be used to handle subsystems and components that are removed and reinstalled in the module and service building primarily during maintenance of the PBMR power plant. These components are to be removed or reinstalled through predetermined access routes into and out of the buildings. Initial installation of components during the construction stage, and removal of components during the decommissioning stage, are not generally included in the EHS. The EHS will, however, also be used for initial installation or decommissioning where economically and technically feasible.

The system will consist of the following subsystems:

- The EHS for the Reactor Cavity Area shall consist of a motorized, rotating gantry installed inside the reactor cavity above the reactor.

- The system concept for the Lay-down Area is expected to be an overhead electrically-driven longitudinal and cross-travelling crane with hanging pendant control accessible from the lay-down floor.

- The rest of the subsystems of the EHS will be standard off-the-shelf items, and will not be classified as safety systems.

7.   AUTOMATION SYSTEM (INSTRUMENTATION AND CONTROL SYSTEMS)

7.1   General

The PBMR Automation System provides automated plant protection, monitoring and control. The main control room is located within the PPSB. A module control room is located within the module.

The Automation System ensures that the plant is operated within defined operating margins. Monitoring, with sufficient redundancy of operating variables, ensures that incipient malfunctions are detected and that appropriate action is taken.

7.2   Subsystems

The Automation System is comprised of the following subsystems:

- Reactor Protection System (RPS);

- Post-event Instrumentation (PEI);

- Equipment Protection System (EPS);

- Operational Control System (OCS);

- Training Simulator;

- Seismic Monitoring System;

- Meteorological Monitoring Station;

- Radiation Monitoring System; and

- Access Control and Security System.

7.2.1   Reactor protection system

The RPS is an independent digital protection system provided for protection of the reactor. The RPS monitors selected process variables, compares the sensed values to preselected levels, and as required, commands and initiates predetermined safety-related protective actions. The RPS initiates reactor trip with the control rods and the shutdown rods, and the insertion of the RSS.

7.2.2   Post-event instrumentation

The PEI is a system of hardware and software provided to sense, record and display a subset of process and plant variables during normal operation, and during and after an event. Information from the PEI is purely informative. The PEI initiates no automated control.

7.2.3   Equipment protection system

The EPS is a programmable system provided for protection of the MPS (excluding the reactor). The EPS is capable of performing its functions with a higher integrity level than provided by the OCS.

7.2.4   Operational control system

The OCS is an industrial programmable control system for automated plant control, the monitoring of plant and process variables, and data storage. The OCS also provides a diverse platform, on which RPS functionality can be duplicated, but with different setpoints and actuation (e.g. reactor control rods are inserted in a controlled fashion, not dropped in). The subsystems of the OCS are as follows:

7.2.4.1 Power plant OCS

The Power Plant OCS monitors and controls, stores and retrieves data, and provides Human-machine (HMI) functionality for the plant outside the module. The Power Plant HMI is located in the main control room.

7.2.4.2 Module OCS

The Module OCS monitors and controls, stores and retrieves data, and provides HMI functionality for the Module Plant in both the module control room and the main control room.

7.2.4.3 Video display system

The Video Display System is integrated with the OCS, and provides video camera monitoring of selected plant areas, with recording and playback capability.

7.2.5   Training simulator

The Training Simulator is for operator training.

7.2.6   Seismic monitoring system

The Seismic Monitoring System senses, records and displays seismic activity.

7.2.7   Meteorological monitoring station

The Meteorological Monitoring Station senses, records and displays meteorological conditions.

7.2.8 Radiation monitoring system

The Radiation Monitoring System is a subsystem of Radiation Protection (RP), which consists of radiological monitoring equipment. The system measures radiation at relevant points in and around the plant to determine radiation exposure of operating staff and radiological discharges to the environment. The system provides prompt, reliable and accurate indication of radiation and of airborne activity levels in operating areas, and is fitted with alarms to indicate significant changes in levels. The equipment is capable of providing reliable remote indication and alarming.

7.2.9 Access control and security system

The Access Control and Security System is a plant-wide integrated system for:

- prevention of unauthorized entry to or exit from various locations;

- prevention of the unauthorized introduction into or removal of items from the premises;

- visual monitoring and recording of areas;

- intrusion detection; and

- personnel timekeeping and accountability.

7.3 Role of the Operator

The OCS supports a hierarchical control structure, which provides operators with access to various levels of control. Control level access is permitted in accordance with the authorization level of the operator.

The RPS and EPS perform all their protective functions in an automated manner.

The following control rooms are provided:

- Main control room in the PPSB. All modules and common plant services control such as high voltage yard switching is performed from this control room. In addition, fire protection, PEI, RPS, seismic and meteorological information is provided to the operator. Dedicated reactor shutdown facilities are also provided.

- Module control room in each module. This control room provides for the control of activities during initial commissioning of a module, during a major module outage, and during the re-commissioning of a module after a major outage. Simultaneous operation from the two control rooms will be prevented.

A dedicated habitable module shutdown room is also provided in each module for reactor shutdown and PEI information display.

8.   ELECTRICAL SYSTEM

8.1   General

The Electrical System consists of the Module Electrical System (MES) and the Power Plant Electrical System. The electrical system, subsystems or components are not nuclear safety-related and total loss of electrical supply has no detrimental effect on the integrity of the fuel.

The electrical design adheres to the power station and industrial electrical system design practices, and will comply with the relevant plant safety standards and legislation. All switching components will be suitably rated for the expected operating duty and fault level currents.

8.2   Off-site Power Supplies

Two off-site power supply connections are provided. The main off-site connection is required for exporting the electrical power generated by the module and is connected to the generator transformer.

The alternative off-site power supply is independent of the main off-site power supply and will supply the plant distribution power when the main off-site connection is not available.

The generator supplies, under normal operating conditions, the plant distribution power via the module transformer.

8.3   On-site Power System

8.3.1   Module electrical system

The MES provides to the module during all operational modes and consists of the following subsystems and components:

- Generator transformer.

- Module transformer which supplies power to the Module Electrical Distribution System.

- Module Electrical Distribution System, which distributes power to the plant auxiliaries within the module and consists of auxiliary transformers, distribution boards, cabling and uninterruptible power supplies.

8.3.2   Power plant electrical system

The Power Plant Electrical System provides power to the loads not associated with any particular module. The Power Plant normally derives its power from the MES and consists of the following subsystems:

- The Power Plant Distribution System, which distributes power to the plant auxiliaries within the module and includes the auxiliary transformers, distribution boards, cabling and uninterruptible power supplies.

- Two medium voltage diesel generators, which supply power to essential loads during an extended power outage (i.e. loss of both off-site power supplies), and are also suitably rated for black-starting of the MPS.

9.   SAFETY FEATURES

9.1   Safety Principles

The PBMR is based on a simple design with passive safety features that require no human intervention, and that cannot be bypassed or rendered ineffective.

9.1.1   Reactor neutronic stability

The PBMR achieves this by demonstrating that the reactor is self-stabilizing due to a neutronic equilibrium that is dependent on temperature. As the temperature of the reactor increases, the neutronic power output decreases.

Pebble bed reactors exhibit a strong negative temperature coefficient that acts as an effective barrier to limit maximum temperatures of the fuel. The main components are the fuel, the moderator and the reflector coefficients, of which only the reflector coefficient is positive. The temperature coefficient remains negative over the entire temperature range of the reactor. It is not constant over the full range, but attains a minimum value just below the operating temperature. This means that, when the temperature exceeds the operating limit, the coefficient that limits the excursion will become even stronger. On the downside, the same is true when a severe under-cooling event takes place. In that case, the reactivity will rapidly increase until the temperature starts to increase again.

9.1.2   Thermohydraulic stability

The reactor core has a relatively low power density (< 4.5 MW/m^3) and tall, slender geometry which optimizes heat transfer capability. This implies that the integrated heat loss capability from the reactor exceeds the decay heat production of the core under all conceivable accident conditions. This means that there are no credible events for which the peak temperature reached in the core during the transient will exceed the safe operating temperature of the nuclear fuel.

The possibility of a 'Core Melt' scenario due to a reactivity or heat-up event is thus impossible.

The use of helium as a coolant, which is both chemically and radiologically inert, combined with the high temperature integrity of the fuel and structural graphite, allows for the use of high primary coolant temperatures (900 °C) that yield high thermal efficiencies.

With these high temperatures, the use of a CCGT is appropriate. It results in an increased efficiency over a steam plant, thus reducing the output-specific capital cost.

9.1.3   Inherent safety aspects of the PBMR

Representative of a new generation of advanced reactors, the PBMR is characterized by a series of inherent safety properties. These characteristics are summarized as follows:

- The use of graphite as fuel element cladding/moderator and core structural material/reflector means that a core melt situation can be ruled out, because of the large difference existing between the normal, average operating temperature (1 095 °C) and the maximum tolerable temperature (2 200 °C for the fuel).

- The large thermal inertia enhanced by the big volume of graphite used in the core and reflector ensures slow temperature transients.

- The limited power density, coupled to small particles of fuel, and the good thermal conductivity of graphite as the major component in the guaranteed heat removal chain, ensure that the fuel element temperature does not exceed 1 600 °C, even in the event of direct cooling failure. Fission product release due to the failure of fuel particles occurs at much higher temperatures. Decay heat can be removed solely by means of conduction and radiation. In the PBMR design, heat is transferred to an extended surface cooler outside of the steel vessel.

- Use of a single-phase medium, helium, as coolant in a graphitic environment, is another safety feature. Helium is chemically inert and does not react with graphite or the metallic core components. Helium cannot be activated with the exception of trace amounts of He-3. Furthermore, the neutron absorption cross-section is very small, thus eliminating the possibility of reactivity addition through coolant loss. In helium, no abrupt changes brought about by phase transition are experienced, thus ensuring elimination of sudden pressure changes that could cause damage to the PB.

- The use of coated particles in the fuel elements results in low levels of contamination in the primary circuit, thus ensuring low radiation doses to the operating personnel.

- Regarding the neutron physics, a strong negative temperature coefficient prevails over the entire temperature range of the reactor due to the presence of the large amount of fertile material, U-238. Large power excursions can thus be ruled out due to the self-stabilizing effect.

- The continuous fuelling concept has the advantage of keeping the level of excess reactivity as low as is required. Adding single fuel spheres has a minor effect on reactivity, and any increase can be quickly corrected by ceasing fuelling operations.

9.2 Safety Design Provisions

9.2.1 Physical barriers against the release of radionuclides

The coated particle is the primary physical barrier against radionuclide release. Refer to **Section 3** of this document for details.

9.2.2 Conservatism in radionuclide retention

Although the coated particle is the most important physical barrier against the release of radionuclides, other physical retention mechanisms do exist. These mechanisms introduce a high level of conservatism into the defence-in-depth approach from an engineering point of view, and are mentioned from this perspective. The retention mechanisms are:

- graphite;

- pressure boundary; and

- reactor building.

Many fuel particles are embedded in the graphite matrix of the spherical fuel elements. This graphite has a high capacity for retaining some fission products (i.e. Sr, Rb, Cs, Ba, and rare earths), but is virtually transparent to others (i.e. noble gases).

The primary gas envelope can also be considered a barrier against radionuclide release. However, for the short-lived fission gases, the dominant removal mechanism is radioactive decay. For the condensable fission products, the dominant removal mechanism is deposition or plate-out on the various helium wetted surfaces in the primary circuit.

The reactor building is a reinforced concrete, vented containment building. No leaktight requirement is necessary for this building. In the event of a break in the primary boundary, it is only the very slight gas-borne activity in the primary coolant and a portion of the activity deposited on the surfaces of the primary system that may be released into the reactor building.

Even if the vent opens and fails to close, natural removal mechanisms (including radioactive decay, condensation, fallout, and plate-out) reduce the concentration of the radionuclides in the containment atmosphere, reducing off-site releases.

9.2.3 Accident prevention and mitigation

Simplicity of the reliance on passive safety features and inherent characteristics allow a simple overall PBMR plant design. The PBMR modules are operated as independent units and interaction between them is minimized. The layout of the PBMR eliminates unnecessary components and

systems, which simplifies normal and emergency operating procedures, inspection, testing, and maintenance. Reliance on control room and operating staff is minimized, since no operator actions are required to prevent fuel damage. Similarly, errors by the operating staff cannot upset the safety characteristics of the PBMR.

The continuous fuelling of the reactor implies that no excess reactivity is necessary in order to compensate for burn-up effects. Nevertheless, a certain margin is required for reactor control and to compensate for changes in the xenon concentration following changes in reactor power. A fast-acting control rod system will serve to keep the reactor within normal operating limits.

Reactor cooling is accomplished by the PCU, the reactor unit conditioning system or by the RCCS. The PCU is an active system that operates during power generation and provides the primary shutdown cooling when available.

In the event that active heat removal systems are unavailable, the core design ensures a passive residual heat removal capacity. The core geometry, limited core diameter, low thermal power rating, low power densities, high negative temperature coefficient, and the passive cavity cooling system limit the maximum core and fuel temperatures.

Under these conditions, heat is transferred through the reactor vessel wall by thermal radiation and natural convection to the cooling surfaces of the RCCS. The reactor vessel walls are uninsulated, to facilitate this process.

10.   PLANT ARRANGEMENT

10.1   Plant Layout

Each reactor plant will consist of the following main buildings:

- reactor building;

- heat sink building and structures (dry cooling tower or sea/river cooling);

- control centre (common module control room); and

- electrical yard buildings and structures.

The reactor building is a single concrete building 50 m (165 ft) long, 26 m (85 ft) wide and 42 m (140 ft) high. Approximately half of the building (21 m) will be below grade.

Personnel access to the main plant buildings is through a service centre. If multiple modules are constructed on a site, only one service centre per 10 modules is required.
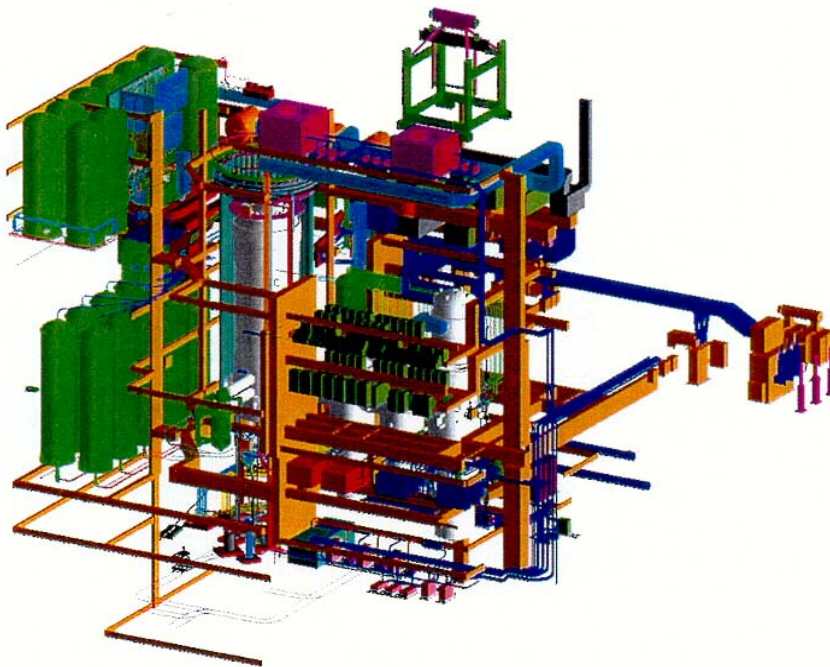

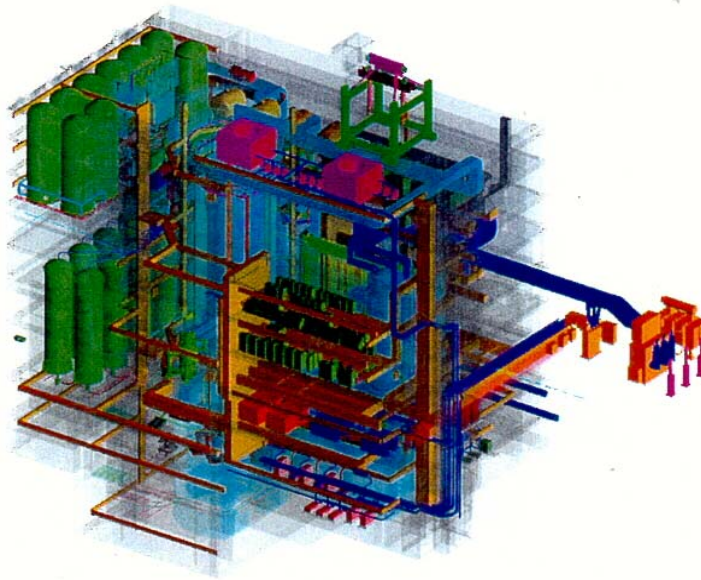**Figure 20: PBMR MAIN POWER SYSTEM WITH SUPPORT SYSTEMS**

Figure 21: BUILDING LAYOUT

10.2   Plant Maintenance

Maintenance and service operations for most of the major equipment will take place at intervals of six years. A significant requirement of the PBMR maintenance and service strategy is to limit radiation exposure to personnel. This requirement is being incorporated into the design of the primary system building by requiring appropriate access to irradiated or contaminated equipment, while keeping radiation exposure ALARA.

The building design provides sufficient space (service hall) for the complete removal of components (e.g. turbo-compressors, PT, recuperator, etc.). Limited decontamination and hot workshop facilities are also provided. However, major equipment will be maintained offsite.

10.3   Description of the Module Building

The PBMR module is a reinforced concrete structure designed to support the MPS and all auxiliary equipment required for the generation of power. The building ensures that a controlled environment can be maintained within, and provides protection for the mechanical and electrical plant.

The modular concept of the PBMR is such that the plant, auxiliary systems, structures and supporting infrastructure can be constructed and operated on most sites and under the majority of

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environmental conditions anticipated around the world. The design, fabrication and operation of the plant systems will be standardized and no major changes to these systems are foreseen.

The services building is designed as the operational centre for the PBMR and will house, inter alia, the control room, health physics control, workshops, offices and stores. However, the services building has limited safety functions, and hence, is not designed to the same criteria as the PBMR building.

10.4   Layout of the Module

The layout of the PBMR building is designed to facilitate the installation of plant, and the access to and maintenance of the installed plant under operating and outage conditions. This will include the provision of maintenance laydown areas. The layout affords radiation protection to the operating and maintenance personnel by means of appropriate shielding of systems and components containing radioactive materials and the reduction of human activity in radiation fields. Radiation zoning will be provided to ensure the most convenient ranges (high, medium and low) are together without mixing.

The layout also makes provision for the storage of spent fuel for the 40-year operating life cycle of the PBMR and, after shutdown of the plant, for interim storage over an additional 40 years.

The layout is also designed to facilitate the concept of individual modular construction whereby up to 10 PBMR modules can be built adjacent to one another, and so minimize the overall size of the unit. This concept enables a module to be in operation whilst the remaining modules are being commissioned and/or constructed.

A containment is included within the external walls of the module building, and this structure encloses the Reactor Unit, comprising the RPV with the core, core internals and reactivity control elements, and the PCU, comprising the HPTU, LPTU, PTG, recuperator and coolers.

Included in the structural requirements of the containment are support to the RPV and PCU, seismic resistance, and shielding. It also forms a second barrier to externally-generated, design basis events, and in the case of internally-generated design basis events, it constitutes the primary barrier.

The containment is defined as a vented, high leak rate, containment which normally operates at lower than atmospheric pressure. Any increase in pressure within the containment, due to a range of design basis breaches in the PPB, is relieved by venting to atmosphere. Small leaks are leaks having a release rate that can be vented by means of the HVAC system. Medium to large leaks or breaks are vented through a dedicated pressure relief shaft to atmosphere. The design of the

pressure relief shaft is such that a quick-acting valve in the HVAC system closes to protect the HVAC system, and a rupture panel in the depressurization route opens at a pre-determined pressure, allowing the gas to escape to atmosphere. After release of the excess pressure, the shaft is closed automatically by a damper mechanism. A manual back-up closure mechanism is provided should this damper fail to operate. After closure of the pressure relief shaft, the building integrity is restored and the HVAC is allowed to resume the conditioning of the environment inside the containment.

10.5 Design Aspects of the Module

For the design of the PBMR module building, it is required that each system be investigated to determine the normal operating, extreme and upset conditions. The effect of these conditions will be translated into physical concentrated and/or pressure loads, thermal loads, dynamic and/or impact loads, which can be directly used in the stress analysis of the buildings. In cases where extreme forces develop under upset conditions, mitigating measures may be implemented to reduce the load rather than to design for its full effect. A typical example of this is provided by the blast release panels which will be incorporated into structural elements of the module to mitigate the effects of overpressure on the structure and plant systems as a result of a depressurization of the high-pressure system. Sufficient redundancy will be built into the structure to ensure its integrity in the event of such extreme or upset events.

A dynamic analysis of the building will be undertaken to evaluate the effects of base excitation on plant systems due to the design basis earthquake. For the seismic design of plant and systems supported in the buildings, it is required that response spectra and time histories be developed at the various floor levels. The RPV and MPS are located close to the centre of gravity of the module, to reduce the effects of seismic induced torsion. In determining the dynamic response of the module building under seismic excitation, the effects of the foundation stiffness will be taken into consideration. The effects of soil structure interaction will also be assessed.

The stiffness of the structure is such as to limit excessive differential displacements during static and dynamic loading, especially at the locations where plant systems are supported. The natural frequencies of the buildings are selected to avoid amplification of the plant dynamic load effects.

The philosophy of design is to establish and use enveloping characteristics for the various environmental parameters, and thereafter to demonstrate that the individual site-specific parameters fall within the envelope.

The excavation for the module building is to be designed taking cognizance of the engineering properties of the soils and the bedrock and the level of the water table.

The foundation of the module building will be designed to adequately support the PBMR under all load conditions and combinations. The effects of unloading and reloading during the excavation, de-watering, construction and backfilling phases, together with an estimation of the settlement of the foundation, will be assessed taking cognizance of the variation of the subsurface materials with depth. The stability of the foundation will be assessed in terms of bearing capacity, overturning, sliding and uplift under hydrostatic pressure.

10.6   Siting Aspects of the Module

In assessing the hazards at the PBMR site, the following data are collected:

- meteorological data;

- seismological data;

- environmental data;

- corrosion potential data;

- cooling water data; and

- hydrological data.

In order to finalize the site layout and establish extreme loading conditions, the following site hazard studies are undertaken:

- site-specific seismic hazard assessment including a seismotectonic study;

- tsunami/seiche hazard assessment;

- flooding hazard assessment;

- internal missile hazard assessment;

- external missile hazard assessment; and

- other hazard assessments including explosion and fire.

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